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A REVISION OF THE SEQUENCE AND STRUCTURE OF THE PRE-KEWEENAWAN FORMATIONS OF THE EASTERN GOGEBIC IRON RANGE OF MICHICAN

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INTRODUCTORY STATEMENT

This paper is a brief presentation of the main results of recent studies of the geology of the Gogebic iron range in Michigan from T. 47 N., R. 45 W., east to Gogebic Lake, a distance of 16 miles.

Former interpretations of the geology are based almost entirely on early investigations of the United States Geological Survey[1] recently summarized in *Monograph 52*. Prior to this work four years of study of the pre-Cambrian of the region south and east of Gogebic Lake to the Iron River district, including 38 townships adjacent in northern Wisconsin, by the senior writer and his assistants had failed to establish a satisfactory basis of correlation with the rocks of the Gogebic Range. Inasmuch as recent drilling for iron ore has supplied important information, unavailable to

[1] C. R. Van Hise and R. D. Irving, *Monograph 19, U.S. Geol. Survey.*

earlier workers in this field, it was thought that a field study of the eastern Gogebic iron range would probably alter former interpretations of the geology and furnish a basis of correlation with the pre-Cambrian terranes of adjacent territory.

The results of the seasons' studies are more satisfactory than we had anticipated and are of considerable importance to the progress of pre-Cambrian geology of the Lake Superior region. This is our excuse for presenting them in preliminary form in advance of a more thorough treatment.[1]

We acknowledge our indebtedness to Dr. C. R. Van Hise for placing in our hands his early field notes and plats, to Dr. C. K. Leith for helpful suggestions in field conference, to Mr. Robert Selden Rose, of Marquette, and to the Presque Isle Mining Company for records of drilling and underground exploration.

SUMMARY OF THE GEOLOGY BASED ON EARLIER WORK

Van Hise and Leith have recently presented the views of the United States Geological Survey[2] which may be briefly summarized.

The Huronian rests on the Archean with profound unconformity and is represented by two unconformable sedimentary groups, the Upper and the Lower Huronian, which are in approximate structural parallelism and dip steeply northward beneath the Keweenawan.

The Archean comprises a green schist series (Keewatin) intruded by granite (Laurentian).

The Lower Huronian has two members, a basal quartzite (Sunday) and an upper cherty dolomite (Bad River).

The geology of the "Upper Huronian (Animikie) Group of the Eastern Area" is summarized in the following words:

> In the eastern part of the district—that is, from about 6 miles east of Sunday Lake to Gogebic Lake—the Upper Huronian rocks have an exceptional character. In the larger part of the district the conditions were those of quiet sedimentation, but in the eastern area throughout the greater part of the Upper Huronian there was continuous volcanic action. In consequence the

[1] R. C. Allen and L. P. Barrett, "Contributions to the Pre-Cambrian Geology of Northern Michigan and Wisconsin," *Publication 18, Michigan Geol. Survey* (in press).

[2] *Monograph 52, U.S. Geol. Survey.*

rocks are lava flows, volcanic tuffs, conglomerates, agglomerates, and slates, with all sorts of gradations, just such as one would expect if a volcano rose in a sea and volcanic action continued for a great period. Naturally in this area it is not possible to map any continuous sedimentary belts. The dominant rocks are greenstone conglomerates and lavas and massive eruptives. The uppermost formation for the extreme eastern part of the area is ferruginous slate. This ferruginous slate, though dominantly clastic, contains narrow bands of non-clastic sediments such as chert, cherty ferro-dolomite, ferro-dolomitic chert. It is believed that the ferruginous slate is probably at the same horizons as the Ironwood formation to the west and that its dominant fragmental character is due to the presence in this area of one or more volcanic mountains which arose above the water and upon which the waves were at work after the close of the period of active volcanic outbreaks.

SUMMARY OF THE WRITERS' CONCLUSIONS

The writers' most important conclusions, in so far as they differ from those of the earlier writers as summarized above, may be stated briefly as follows:

1. *Huronian.—There are three unconformable sedimentary groups in the Huronian series.* The formations heretofore included in the Upper Huronian (Animikie) group are divisible into two groups separated by an unconformity of the first magnitude. For the superior group we propose the name Copps, in recognition of the important exposures of its basal horizons near the old Copps mine.

2. *Archean.—The granite heretofore described as Laurentian not only intrudes the Keewatin but also cuts across two great unconformities into the Animikie group.* Some of the granite may be Laurentian, but we have not been able to so correlate any of it.

3. *The unconformity between the Copps and Animikie groups is one of great angular and erosional magnitude* and is of greater importance in this district, measured by criteria for evaluation of breaks in pre-Cambrian sedimentary successions, than either the unconformity separating the Keweenawan and Huronian or the one separating the Animikie and Lower Huronian.

For convenience of reference and greater clearness in the discussions which follow we introduce the successions of the United States Geological Survey and the writers' in parallel columns.

CORRELATION TABLE I

GOGEBIC IRON RANGE

	By U.S. Geological Survey, 1911		By Michigan Geological Survey, 1914
	West of center of T. 47 N., R. 44 W.	East of center of T. 47 N., R. 44 W.	East of T. 47 N., R. 45 W.
Quaternary System Pleistocene series	Glacial deposits	Glacial deposits	Glacial deposits
Cambrian System		Unconformity Lake Superior sandstone	Unconformity Lake Superior sandstone (doubtful)
Algonkian System Keweenawan series	Unconformity Gabbro, diabase, basic lavas, conglomerate, etc.	Unconformity Gabbro, diabase, basic lavas, and interbedded sandstone and conglomerate	Unconformity Gabbro, diabase, basic lavas, interbedded sandstone and conglomerate and basal conglomerate Unconformity Copps formation. Ferruginous slate, graywacke, chert, and basal conglomerate
Huronian Group Upper Huronian (Animikie)	Unconformity Greenstone intrusives and extrusives Tyler slate Ironwood formation (iron-bearing) Palms formation	Unconformity Extrusive and intrusive greenstones Palms and Ironwood formations represented by ferruginous slate, graywacke, and quartzite	Unconformity Granite Extrusive and intrusive greenstones Ironwood formation (iron-bearing) Palms formation
Middle Huronian Lower Huronian	Unconformity Bad River limestone Sunday quartzite	Absent	Unconformity Bad River limestone Sunday quartzite
Archean System Laurentian series	Unconformity Granite and granitoid gneiss	Unconformity Granite and granitoid gneiss	Unconformity
Keewatin series	Greenstone and greenschist	Greenstone and greenschist	Greenschist

ARCHEAN SYSTEM

Rocks of Archean age are confined, in the territory under discussion, to the fine-grained chloritic schists (Keewatin) lying unconformably beneath the Sunday quartzite in T. 47 N., R. 44 W. In the maps accompanying the reports of the United States Geological Survey the hornblende and mica schists lying south of the Huronian sediments in T. 47 N., R. 43 W., are included in the Keewatin, and the extensive area of acid intrusives, here termed the Presque Isle granite, is placed in the Laurentian. We believe that the Presque Isle granite intrudes the Middle Huronian and that the schists in T. 47 N., R. 43 W., heretofore correlated with the Keewatin, are phases of the Palms formation, the metamorphism being induced by granitic intrusion.

THE ALGONKIAN SYSTEM

HURONIAN SERIES

Lower Huronian group

The Lower Huronian comprises two formations, viz., the Sunday quartzite and the Bad River limestone, exposures of which are limited to the south half of sections 17 and 18, T. 47 N., R. 44 W.

The Sunday quartzite is grayish white to pink, about 150 feet thick, and carries a thin basal conglomerate holding fragments of the underlying Archean (Keewatin) greenschist. It inclines gently (30°) across the almost vertical plane of schistosity in the subjacent schists.

The Bad River formation is a cherty dolomite about 400 feet thick. It is conformable through gradational phases with the underlying Sunday quartzite and is unconformably overlain by the Upper Huronian (Animikie) group.

Upper Huronian (Animikie) group

The Animikie group is represented by a basal quartzite (Palms), an iron-bearing member (Ironwood), volcanic conglomerates, breccias and flows, and intrusive granite and greenstone.

On recent maps of the United States Geological Survey the Palms and Ironwood formations are carried eastward as cartographic

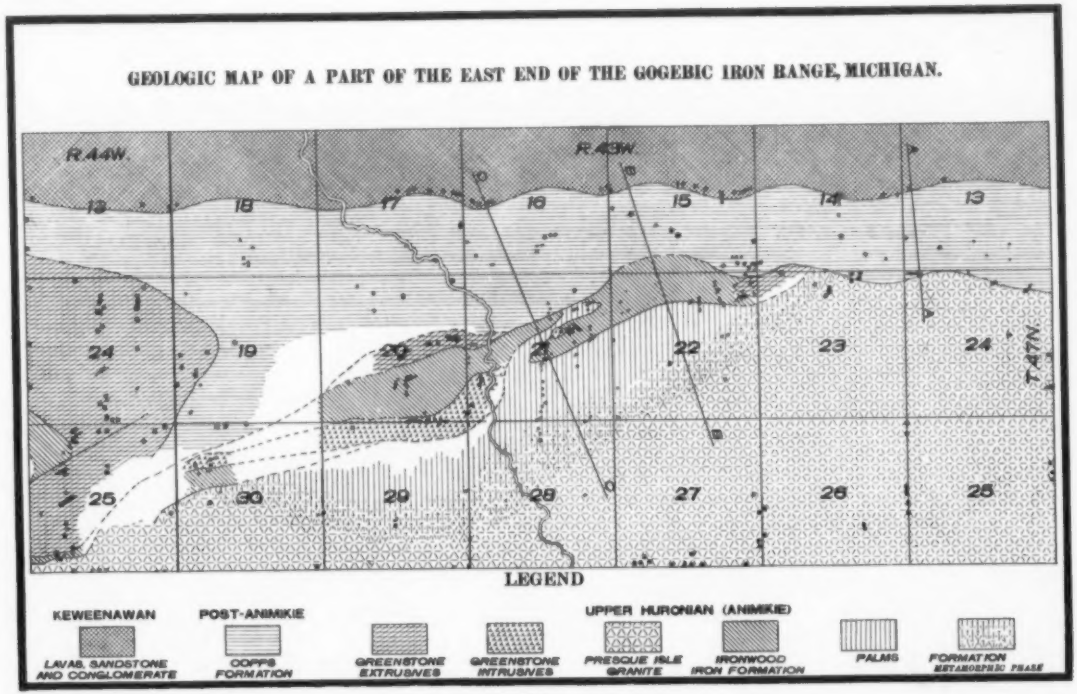

GEOLOGIC MAP OF A PART OF THE EAST END OF THE GOGEBIC IRON RANGE, MICHIGAN.
R.44W.
R.43W.
T.47N.
LEGEND
KEWEENAWAN
LAVAS, SANDSTONE AND CONGLOMERATE
POST-ANIMIKIE
COPPS FORMATION
GREENSTONE EXTRUSIVES
GREENSTONE INTRUSIVES
UPPER HURONIAN (ANIMIKIE)
PRESQUE ISLE GRANITE
IRONWOOD IRON FORMATION
PALMS
FORMATION METAMORPHIC PHASE

FIG. 1

units only to section 22, T. 47 N., R. 44 W., where a new unit representing the ferruginous slates is introduced to carry their combined stratigraphic horizons east to the extremity of the range, although isolated patches of iron formation are correlated with the Ironwood.

The writers' studies indicate very clearly: (1) the extension of the Palms and Ironwood formations eastward 7 miles beyond the point at which they are dropped as cartigraphic units from the

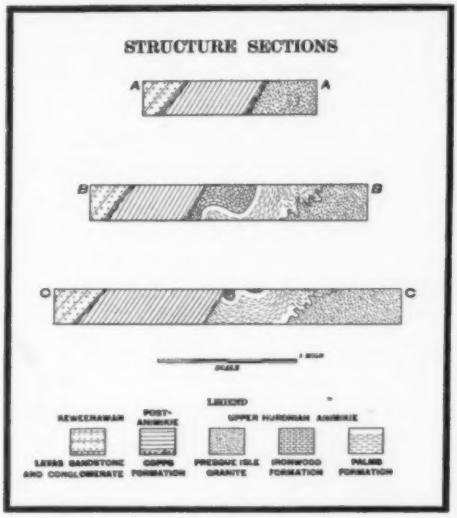


FIG. 2

maps of the United States Geological Survey; (2) these formations disappear, *not through lithologic gradation* into ferruginous slate, but through *abrupt truncation by a superior unconformable series;* and (3) that *these formations are intruded by the granite which appears on these maps as Archean* (Laurentian).

The Palms formation.—The Palms formation west of section 22, T. 47 N., R. 44 W., contains about 400 feet of graywacke and slate with interbedded thin bands of quartzite which become gradually more prominent in the upper horizons and grade into a

top layer of heavily bedded quartzite 50 feet thick. The basal horizon is a conglomerate from 1 to 10 feet thick. East of this township the massive upper quartzite is generally persistent, but the lower horizons grade irregularly into micaceous and hornblendic schists toward the contact with the intrusive Presque Isle granite in which, so far as we have determined, the base of the Palms is involved. The former correlation of the metamorphosed lower horizons of the Palms formation with the Keewatin is based on early field studies and has unfortunately been carried without revision into later work.

The Ironwood formation.—The iron-bearing member overlies abruptly but conformably the heavy upper quartzite of the Palms formation. A thin basal layer is in some places finely detrital.

The Tyler slate, which overlies the Ironwood formation west of Sunday Lake, is abruptly cut out at the great Wakefield overthrust and does not appear on the east end of the range. From Wakefield east to section 16, T. 47 N., R. 44 W., the Ironwood formation is overlain by the Keweenawan series, and beyond this locality with the Copps group, by which it is trunkated and cut out in the N.W. ¼ of section 22, T. 47 N., R. 43 W.

Except where altered by intrusives, to which further reference will be made, the Ironwood formation is made up of ferruginous chert and slate, iron ore, cherty iron carbonate, and interbedded black and gray slate. In T. 47 N., R. 44 W., it is split, 200 feet above its base, by a great graywacke-slate member about 500 feet thick, which is identical in character with the slate forming the so-called "secondary foot wall" of the Brotherton, Sunday Lake, and Castile mines at Wakefield and is apparently at the same stratigraphic horizon. The inclusion of this slate member for a distance of not less than six miles east of Sunday Lake gives the Ironwood formation a maximum thickness of 1,300 to 1,400 feet.[1]

[1] Further observation west of Sunday Lake in both Michigan and Wisconsin indicates that the base of the Ironwood is conglomeratic throughout almost its entire extent. An intra-formational conglomerate and quartzite, first observed by geologists of the Oliver Iron Mining Company, occurs in the Pabst mine at Ironwood, a little less than 500 feet vertically above the Palms quartzite. A similar conglomerate has been observed at about the same horizon by W. O. Hotchkiss, state geologist of Wisconsin, in some of the mines on the Wisconsin end of the range. So far

Extrusive and intrusive greenstones.—Abundant exposures of greenstone occur throughout four square miles in T. 41 N., Rs. 43 and 44 W., and in a few other scattered small areas. These are mainly of extrusive types, but some coarsely crystalline intrusive equivalents are associated with them. Later dikes of diabase, probably of Keweenawan age, intrude the greenstone. The intrusives are mainly volcanic agglomerate and breccia, but in association with them are amygdaloidal lavas, tuffs, and some slate and conglomerate. An interesting feature of the lavas is a clearly indicated genetic relation to inclosed bands and irregular masses of red jasper. Basic flows with well-developed amygdaloidal tops are interbedded with the Ironwood formation from as far west as the Palms mine eastward to near Wakefield but are thus far not known to occur on the east end of the range.

The volcanics are closely associated with the Ironwood formation, in part interbedded in its upper horizons but in greater part superimposed. That they are unconformably overlain by the Copps group is an inference based on general field relations and the inclusion of pebbles of the volcanics in the Copps conglomerate rather than direct observation of contacts. Wherever the Copps group is in juxtaposition to the volcanic greenstones it invariably dips away from them.

The evidence indicates that volcanism was active on sea and land from middle Ironwood time, continuing perhaps for an indefinite period after the close of sedimentation.

The Presque Isle granite.—We propose the name Presque Isle granite for the rocks described by Van Hise and Irving as constituting the "Eastern Laurentian Granite Area."[1]

as observations have gone it may be said that this conglomerate bears no structural discordance to the underlying member of the Ironwood formation.

Mr. Fred Wolff has recently described the occurrence of a conglomerate in middle horizons of the Biwabik formation on the Mesabi iron range (*Engineering and Mining Journal*, C, No. 3). Inasmuch as the Ironwood and Biwabik formations are believed to be equivalent, this conglomerate may indicate a widespread disconformity. However, this disconformity is of very minor significance as compared with the profound unconformities which separate the Upper Huronian from the Animikie and the Animikie from the Lower Huronian, and, so far as known, has little importance in the consideration of the major subdivisions of the Huronian series.

[1] *Monograph 19, U.S. Geol. Survey.*

In a later publication[1] we will introduce evidence, based on field surveys and drilling operations, in support of the correlation of the Presque Isle granite with those occurring southwestward and southeastward to the state line in Michigan and over an adjacent large area in northern Wisconsin, possibly including the later intrusive granites of the Florence and Menominee districts, heretofore doubtfully correlated with the Keweenawan.[2] The close of Animikie time over this great area seems to have been characterized by batholithic intrusions of granite on a grand scale, comparable in the pre-Cambrian of the Lake Superior region to those of Laurentian time.

The Presque Isle granite is predominantly an acid type which varies through gradational phases into syenite and diorite. The rocks are mainly massive, but marked gneissosity is not an uncommon structural feature.

Relations to Upper Huronian (Animikie) group.—The inference that the Presque Isle granite is intrusive in the Animikie group rests on the following evidence:

1. The lower members of the Palms formation show a gradual transition in proportion as they approach the granite to micaceous and hornblendic schists and gneisses with obliteration of clastic structure.

2. The Palms and Ironwood formations are characterized by abundant quartz veins and the Palms formation also by veins of aplite and pegmatite which become increasingly prominent toward the granite.

3. The Ironwood formation becomes amphibolitic, magnetitic, and schistose in proportion to approach of the granite.

4. The Palms formation is apparently absent in the vicinity of section 25, T. 47 N., R. 44 W., where the Ironwood formation is an amphibole-magnetite schist and is separated by only a short distance from exposures of the granite.

The foregoing relations may be illustrated by reference to a few important localities. The best exposed section of the Palms formation

[1] "Contributions to the Pre-Cambrian Geology of Michigan and Northern Wisconsin," *Publication 18, Michigan Geol. and Biol. Survey* (in press).

[2] *Monograph 52, U.S. Geol. Survey.*

is adjacent to a north-south line from the center of section 21 southward about one mile to the granite near the center of section 28, T. 47 N., R. 43 W. The upper quartzite member underlies the Ironwood formation near the center of section 21. Proceeding southward there are numerous exposures and test pits showing the characteristic lower horizons of interbedded quartzite, quartz slate, and graywacke, complexly folded and cut by numerous quartz veins. From about 800 paces south the veins of aplite and pegmatite appear and the rocks become noticeably micaceous and hornblendic, with a gradual disappearance of clastic structure until they give place to those more properly described as mica-hornblende schist and gneiss. This mineralogical transition is accompanied by a gradual increase in the size and number of the aplitic and pegmatitic veins. The granite first occurs in intimate interbanding with hornblende gneiss and finally excludes it entirely.

In the vicinity of section 25, T. 47 N., R. 44 W., and section 30, T. 47 N., R. 43 W., the Presque Isle granite has apparently eaten its way upward through the upper heavy quartzite of the Palms into the Ironwood formation, and has very probably displaced or absorbed both of these formations in the E. $\frac{1}{2}$ of the former township. In these localities the Palms formation is apparently absent and the Ironwood formation is represented by amphibole-magnetite schist, which in section 25 is separated from hornblende syenite by a narrow strip about 150 feet wide in which there are no exposures.

In the workings of the Presque Isle mine on section 21, T. 47 N., R. 43 W., a conspicuous feature of the Ironwood formation is the occurrence of an unusual abundance of anastomosing quartz masses and veins. Pit dumps and drill records indicate that this feature is not local but general throughout the iron formation in this township. This phenomenon coupled with other evidence of granitic intrusion has considerable significance.

We take care to state that complete mineralogical gradation of either member of the Animikie into granite cannot be observed in any single exposure, but that such gradation is a fact and accounts for the absence of identifiable contacts is a conclusion which rests on field observations which admit of no other interpretation.

Copps group (Post-Animikie).—The Copps group is the name which we propose for the rocks occupying the area which is mapped and described in *Monograph 19, U.S. Geol. Survey*, under the heading "Ferruginous Slates of the Eastern Area." It is composed of a basal conglomerate, overlain by a great thickness of graywacke slate, which is highly ferruginous in the western half of its area and is associated in certain horizons, especially the lower ones, with considerable non-clastic chert and here and there with jasper.

The important member of this formation for purposes of this article is the basal conglomerate. This conglomerate is exposed in many places and shows a characteristic variation in content of matrix and pebbles with the character of the formation on which it rests.

From section 23, T. 47 N., R. 43 W., east to the extremity of the range it is in contact with the Presque Isle granite; the conglomerate here is composed of granite pebbles and bowlders ranging up to 4 or 5 feet in diameter imbedded in a matrix of sideritic arkose, the bowlder content exceeding the volume of matrix. A few pebbles of chert, jasper, quartzite, and greenstone appear in a large exposure near the S.W. $\frac{1}{4}$ of section 24, T. 47 N., R. 43 W., but one mile west of this place, near the old Copps mine, where the Copps formation truncates the Animikie, the granite pebbles have entirely disappeared, giving place to smaller fragments of chert and quartzite, chert predominating, derived from the Ironwood and Palms formations. The matrix here has increased in relative importance and has changed to finely clastic chert and quartz cemented by iron carbonate. North of the center of section 21 and near the N.W. corner of section 19, T. 47 N., R. 43 W., the conglomerate is exposed in test pits. In these localities the matrix has the character of graywacke in which are inclosed numerous small rounded pebbles of chert, jasper, and vein quartz. The conglomerate has also been penetrated by drilling in section 21, T. 47 N., R. 43 W., and, according to J. M. Louggeor, Jr., occurs "all along the north and east edges of the greenstone area" in sections 13, 14, 19, and 24, T. 47 N., R. 44 W.[1]

[1] A thesis on the geography of part of the Gogebic Range. Harvard University, 1915 (unpublished).

Relations of the Copps group to the Upper Huronian (Animikie).— It has been stated that the unconformity separating the Copps and Animikie groups is one of the first order of magnitude. This conclusion rests on the following evidence:

1. The bottom horizon of the Copps group is a true basal conglomerate.

2. The Presque Isle granite intrudes the Animikie but yields bowlders and matrix to the basal conglomerate of the Copps.

3. The Copps group is in great structural discordance with the Animikie.

4. The areal relationships are those of unconformity.

5. Volcanic rocks are characteristic of the Animikie and are not known to occur in the Copps formation.

The only one of these evidences remaining to be discussed refers to the great structural discordance between the Upper and Middle Huronian groups. At this point the reader is referred to the accompanying map and sections which exhibit the areal and structural relationships much more satisfactorily than any amount of written description could possibly do. It should be stated in this connection that the structural sections are based to a great extent on drill records, as are also the areal relationships of the Ironwood and Palms formations in sections 20, 21, and 22, T. 47 N., R. 43 W. It is not held that other interpretations of structure as far as concerns merely the details are not possible, but that those interpretations which have due regard to the facts of occurrence must coincide in major outline and cannot fail to establish the main fact of great structural discordance between the Upper and Middle Huronian groups. The data for structural sections are unusually ample because of the large amount of drilling and test-pitting which has been executed, fortunately in the most critical area, from the geologic point of view, on the east end of the range.

The dominant structure of the Animikie group of the Gogebic Range is that of a simple monocline in approximate structural parallelism with the Keweenawan series. Pre-Keweenawan deformation by folding is conspicuous only in the vicinity of Wakefield and on the east end of the range. Without venturing an opinion as to the vicinity of Wakefield, to which locality our field studies

have not extended, it is clear that the main folding of the Animikie on the east end is not only pre-Keweenawan but also pre-Copps. The cause and the localization of the deformation are referable to batholithic intrusion of granite.

Relations to Keweenawan series.—Studies of the Keweenawan series were limited to the problem of its relation to the Copps group.

The Keweenawan is unquestionably unconformably superimposed on the Copps. The contact is marked in some places by a strong basal conglomerate carrying pebbles and bowlders derived from all of the members of the Copps and Animikie groups. Inasmuch as this conglomerate has not been described, perhaps a brief reference to it will not be out of place here. In sections 14, 15, and 16, T. 47 N., R. 43 W., the base of the Keweenawan is a coarse, firmly cemented, sandstone 50 to 75 feet thick grading into conglomerate near the base. The pebbles of the conglomerate comprise fragments of vein quartz, red slate, quartzite, graywacke, jasper, chert, and iron ore.

Relations to Cambrian (Eastern or Jacobsville) sandstone.—The Eastern or Jacobsville sandstone has been described by other writers as resting unconformably on rocks here designated as the Copps group. This evidence rests on an examination many years ago of exposures in test pits. These pits are now filled and overgrown with brush and we were therefore unable to add anything to existing information.

RELATIVE TO THE BEARING OF CONCLUSIONS ON LAKE SUPERIOR PRE-CAMBRIAN CORRELATIONS

It is not our purpose to anticipate in this paper the following discussion of the bearing of this revision of the geology of the Gogebic Range on the more general problem of the pre-Cambrian correlations. To the student of Lake Superior geology the suggestion will arise that had these relationships been discerned thirty years ago the history of the pre-Cambrian correlations would probably have been markedly different, not only in Michigan but in general.

Any disposition which may be made of the Copps group in the correlations must take into account the magnitude of the uncon-

formity at its base and the bearing on the general problem of the enormous scale of the batholithic granitic intrusions of late Animikie time.

DISCUSSION OF CORRELATION

C. K. LEITH AND R. C. ALLEN

INTRODUCTORY STATEMENT

The non-productive eastern end of the Gogebic Range is folded, faulted, and associated both with intrusive and extrusive rocks. In the lack of sufficient exposures and exploration scarcely more than lithologic mapping was possible when the range was worked over by Irving and Van Hise.[1] Structural mapping was not attempted. In recent years, exploration of this area by drilling has connected some of the isolated outcrops of iron-formation bands and has made it possible to map the area structurally. This has been done effectively by Messrs. Allen and Barrett, who outline their results in the preceding paper. While there are still some parts of the area to which the structure and areal connections are obscure, certain features of exceptional interest from the standpoint of general Lake Superior geology have already been worked out. These are: (1) discovery of the fact that there is an intrusive granite with important metamorphic effects in the supposed eastward continuation of the Gogebic iron formation (Animikie); and (2) the existence of a ferruginous graywacke formation with jasper and chert bands, called the Copps formation, separated from the inferior Animikie series by a great structural unconformity and unconformably below the Keweenawan.

These facts raise interesting questions as to revision of the pre-Cambrian correlation of Michigan, which touch more or less also the correlations of the Lake Superior region as a whole. Leith thinks it possible that the Copps series may be of only local significance and require no general change, but he agrees with Allen that Michigan correlation should be carefully tested to ascertain whether the known facts can be better expressed by a different

[1] *Monograph 19, U.S. Geol. Survey*, 1892.

correlation than that heretofore used. Two main possibilities present themselves: (1) that the Copps represents a fourth Huronian series between the Animikie and Keweenawan; (2) that there are three Huronian series, and that the Copps formation may be equivalent to certain series elsewhere in Michigan, now otherwise correlated.

1. CORRELATION ON THE ASSUMPTION THAT THE COPPS FORMATION REPRESENTS A FOURTH HURONIAN SERIES BETWEEN THE ANIMIKIE AND KEWEENAWAN

If the Copps series be regarded as the remnant of a much larger series that has everywhere else been removed by erosion, it may be necessary to give it a position of the same general order as that of the Animikie or Upper Huronian, with the result that the Huronian series of Lake Superior become relatively lowered throughout the column, which would involve some changes in names. There would then be four Huronian series instead of three. The evidence, as it is, seems to afford too slight a basis for moving downward all the rest of the formations and introducing sweeping changes in nomenclature. The names now used have come to have well-understood significance, and well express the principal similarities and relationships of the pre-Cambrian series. When the extent and relationships of the Copps series can be more fully demonstrated it may be desirable to introduce such sweeping changes. To do so now would be premature and would almost inevitably require further changes when the significance of the Copps formation becomes more fully understood.

2. CORRELATION ON THE ASSUMPTION THAT THERE ARE THREE HURONIAN SERIES AND THAT THE COPPS FORMATION MAY BE EQUIVALENT TO CERTAIN SERIES NOW OTHERWISE CORRELATED

Allen and Barrett regard the Copps formation as the equivalent of the Upper Marquette series, the Princeton series,[1] and certain formations in other districts above the Animikie which are believed to be, as in the Gogebic district, below the Keweenawan. Leith

[1] R. C. Allen, "Correlation and Structure of the Pre-Cambrian Formations of the Gwinn Iron-bearing District of Michigan," *Jour. Geol.*, XXII (1914), 560–73.

believes that the evidence thus far available, while suggestive, does not constitute a sufficient basis for throwing over the present correlation, which brings out the main features of succession in common in the different districts, and that a revision introduces difficulties in local correlation quite as great as any in the old correlation. In order to bring out clearly the possibilities in the situation, the two views are presented below respectively by R. C. Allen and C. K. Leith.

A REVISION OF THE CORRELATION OF THE HURONIAN GROUP OF MICHIGAN AND THE LAKE SUPERIOR REGION

R. C. ALLEN

The Huronian group comprises at least three unconformable series of pre-Cambrian sedimentary and associated igneous rocks separated from the younger Keweenawan series by a great unconformity and from the older Archean system by another more profound unconformity. The position of the group has been defined by the United States Geological Survey and by a committee of Canadian and United States geologists[1] (1904) as follows:

Paleozoic		
		Unconformity
	Keweenawan	
		Unconformity
		Upper
		Unconformity
Algonkian	Huronian	Middle
		Unconformity
		Lower
		Unconformity
	Keewatin	
Archean		Eruptive contact
	Laurentian	

Former correlations of the Huronian group as well as the entire pre-Cambrian of the various districts of the Lake Superior region in the United States are mainly the results of detailed field study and mapping by the United States Geological Survey. These

[1] *Jour. Geol.*, XIII (1905), 89–104.

studies have been published in a series of monographs on the most important districts and a final summary covering the entire region.[1]

In 1892 Irving and Van Hise published their completed work on the Gogebic iron range. They believed that the Huronian series in the Gogebic district comprises *two* unconformable series, the Upper and the Lower Huronian, and that the Upper Huronian or iron-bearing series is probably equivalent to the Animikie of the north shore of Lake Superior. In 1896 Van Hise, Bayley, and Smyth issued a monograph on the Marquette iron range. They found here *two* unconformable Huronian series, the *Upper* and the *Lower* Huronian, which were correlated with the *Upper* and the *Lower* Huronian of the Gogebic Range, the Negaunee iron-bearing series of the Marquette Range falling in the lower Huronian. These two works are the origin of the *dual classification* of the Huronian which was gradually extended to cover all of the other districts of the Lake Superior region until A. E. Seaman discovered, about 1902, that the "lower" Huronian of the Marquette Range is divisible by a great unconformity at the base of the Ajibik quartzite. In 1904 Seaman's discovery was formally recognized by an international committee of Canadian and United States geologists which adopted the tripartite classification of the Huronian group.[2] The Negaunee iron-bearing series was separated from the Lower Huronian to form the new Middle Huronian, but the old correlations outside the Marquette Range were preserved. In 1913 Allen accounted for a tripartite division of the Huronian in the Gwinn synclinorium and correlated the Gwinn iron-bearing series with the Negaunee

[1] R. D. Irving and C. R. Van Hise, "The Penoke Iron Bearing Series of Michigan and Wisconsin," *Monograph 19, U.S. Geol. Survey*, 1892; C. R. Van Hise and W. S. Bayley, "The Marquette Iron Bearing Series of Michigan, with a chapter on the Republic Trough, by H. L. Smyth," *Monograph 28, U.S. Geol. Survey*, 1896; C. R. Van Hise, J. M. Clements, W. S. Bayley, and H. L. Smyth, "The Crystal Falls Iron Bearing District of Michigan," *Monograph 36, U.S. Geol. Survey*, 1899; C. K. Leith, "The Mesabi Iron Bearing District of Minnesota," *Monograph 43, U.S. Geol. Survey*, 1903; J. M. Clements, "The Vermilion Iron Bearing District of Minnesota," *Monograph 45, U.S. Geol. Survey*, 1903; W. S. Bayley, "The Menominee Iron Bearing District of Michigan," *Monograph 46, U.S. Geol. Survey*, 1904; C. R. Van Hise and C. K. Leith, "Geology of the Lake Superior Region," *Monograph 52, U.S. Geol. Survey*, 1911.

[2] *Jour. Geol.*, XXII, No. 6 (1914).

iron-bearing series of the Marquette district. In 1914 Allen and Barrett found that the Upper Huronian, as described by Van Hise and Irving, on the east end of the Gogebic Range includes *two* unconformable series separated by a profound unconformity. This discovery has, in their judgment, opened the way for a revision of the correlation of the Huronian group of the Lake Superior region in which some of the difficulties and inconsistencies in the old classification largely disappear.

The new correlation places the Animikie series in the Middle Huronian, rather than in the Upper Huronian as in former correlations. Briefly stated, the steps in the argument are these:

1. The Animikie (iron-bearing) series of the Gogebic Range is the equivalent of the Negaunee (iron-bearing) series which constitutes the Middle Huronian of the Marquette Range; therefore, the Animikie series of the other Michigan districts, Minnesota, and the north shore of Lake Superior is also the equivalent of the Negaunee series, i.e., Middle Huronian.

2. The Negaunee series of the Marquette Range is unconformably overlain by the Upper Huronian. The Ironwood (Animikie) series of the Gogebic Range is also overlain unconformably by a series which is *unconformably beneath the Keewenawan*. This series is equivalent to the Upper Huronian of the Marquette Range. The Animikie is therefore Middle Huronian.

CORRELATION OF THE ANIMIKIE SERIES AS MIDDLE HURONIAN

Correlation of the Ironwood series with the Negaunee series.—The Ironwood (Animikie) iron-bearing series of the Gogebic Range is correlated with the Negaunee (Middle Huronian) iron-bearing series of the Marquette Range because (1) these series occupy identical positions in the Huronian succession of these districts, (2) are essentially similar, (3) are underlain and overlain by essentially similar series, (4) are in practically adjacent territory, and (5) there is substantial evidence of their equivalence through direct connection of the Negaunee series with the Vulcan (iron-bearing) series of the Crystal Falls–Iron River district which bears the same relation to a great granite batholith and its outliers as does the

Ironwood series of the Gogebic Range and its correlatives in the Marenisco and Turtle ranges.

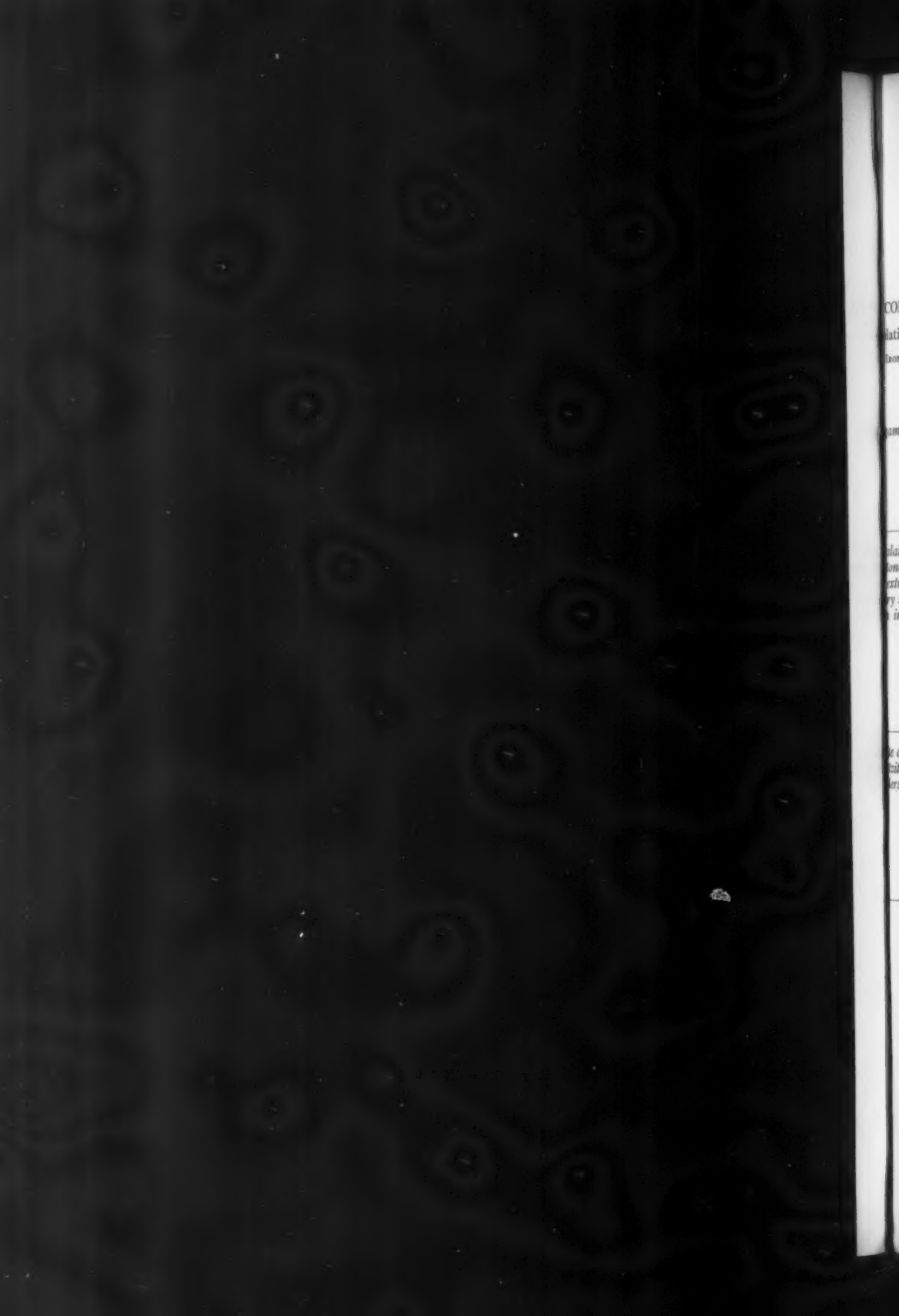
The similarity of the successions in the Gogebic and Marquette districts is striking, and coupled with proximity would ordinarily determine a direct correlation of the similar series occupying identical positions in the group even were there no further evidence of identity.

CORRELATION TABLE III

CORRELATION OF THE HURONIAN GROUP IN THE GOGEBIC AND MARQUETTE DISTRICTS

	Marquette District	Gogebic District
	Greenstone intrusives and extrusives	
	Clarksburg volcanics partly replacing Michigamme slate	Graywacke and slate
Upper Huronian	Michigamme slate carrying iron-bearing lenses (Bijiki schist)	Ferruginous and cherty slates and jasper
	Goodrich conglomerate—quartzite	Conglomerate
	—Unconformity—	—Unconformity—
	(Deep erosion)	Presque Isle granite
		Tyler slate
Middle Huronian (Animikie)	Negaunee (iron-bearing) formation and extrusive greenstone	Ironwood (iron-bearing) formation and extrusive greenstone
	Siamo slate	Palms quartzite and quartz slate
	Ajibik quartzite	
	—Unconformity—	—Unconformity—
	Wewe slate	(Deep erosion)
Lower Huronian	Kona dolomite	Bad River dolomite
	Mesnard quartzite	Sunday quartzite
	—Unconformity—	—Unconformity—
Archean		

The absence of slate above the Bad River dolomite should be considered with the evidence of deep erosion in Middle-Lower Huronian time in the Gogebic district which not only removed the slate if it was ever present there but also the entire Lower Huronian over the greater part of the range. In respect to the Middle



CORRELATION TABLE II

lation on the basis that the Animikie Group is Middle Huronian)

Iron River	Vieux Desert Conover	Manitowish	Turtle	Marenisco
mme slate				
late? *ne intrusives* *trusives* *y slate* *iron forma-*	*Granite* *Slate and schist*	*Granite* *Kyanitic, biotitic, garnetiferous, and graphitic schists* *Amphibole-magnetite rocks*	*Granite* *Greenstone intrusives and extrusives* *Slate* *Iron formation* *Slate* *Quartzite*	*Presque Isle granite* *Greenstone extrusive and intrusives* *Slate* *Iron formation* *Graywacke and quartzite*
e and *zite* *rs forma-*			*Dolomite* *Dolomitic quartzite*	

Marenisco	Gogebic	Cuyuna	Mesabi
	Copps formation		
Presque Isle granite	*Presque Isle granite*	*Basic and acidic intrusives and extrusives*	*Embarrass granite(?)*
Greenstone extrusives and intrusives	*Tyler slate*	*Virginia* (St. Louis) *slate*	*Acidic and basic intrusives*
Slate	*Greenstone extrusives*	*Deerwood iron formation*	*Virginia slate*
Iron formation	*Ironwood iron formation*		*Biwabik iron formation*
Graywacke and quartzite	*Palms formation*	*Slate*	*Pokegama quartzite*
		Quartzite	
			Giants Range granite
	Bad River limestone		*Graywacke conglomerate*
	Sunday quartzite		

	Vermilion	Gunflint Lake	Animikie
c in-			
rma-	*Rove slate* *Gunflint iron formation*	*Rove slate* *Gunflint iron formation*	*Black slate* *Iron formation*
	Granite, dolorites, lamprophyres intrusive into rocks below	*Greenstone and granite intrusives*	*Granite and greenstone* intrusive into rocks below
lom-	*Knike Lake slate*	*Graywacke*	
	Agawa formation *Ogishke conglomerate*		*Slate, graywacke, and conglomerate*

Huronian (Animikie) of these districts the situation is reversed, i.e., the thick Tyler slate formation above the Ironwood series is to be considered with the evidence of deep erosion of the Negaunee series and the development of iron ores on the exposed surface of the iron formation (now represented by the hard ores of the upper part of the Negaunee formation) prior to the deposition of the Upper Huronian. If the correlative of the Tyler slate was ever deposited on the Negaunee formation, it had been removed prior to the deposition of the Goodrich quartzite. The Middle Huronian (Animikie) of both districts is characterized by volcanic activity which continued on into and culminated in the Upper Huronian in the Marquette Range but terminated prior to the deposition of the Copps formation in the Gogebic Range.

There is a strong resemblance of the Copps formation of the Gogebic to the Upper Huronian of the Marquette Range in respect to lithology and order of succession. At the base of these series is a great conglomerate which is overlain by slate and graywacke. Neither series carries a great productive iron-bearing member, but both contain jasper and ferruginous beds near the base, which in the Marquette district are locally iron ore-bearing.

It can hardly be doubted that if Van Hise and Irving had discovered in 1892 the great unconformity at the base of the Copps formation on the Gogebic Range, and Van Hise and Bayley in 1896 the great unconformity at the base of the Ajibik quartzite on the Marquette Range, the correlation of the Huronian group of the Lake Superior region would have been *tripartite* from the beginning and not *dual*, for the correlations have been built up on these two type districts which were earliest studied by the United States Geological Survey. The Ironwood (middle) series would *then* have been correlated with the Negaunee (middle) series because, as above stated, they occupy identical positions in the Huronian succession, are essentially similar, are overlain and underlain by essentially similar series, and are in practically adjacent territory. The character of the reasoning which was employed in correlating the formations in these districts and which resulted in a separation of the similar iron-bearing series in the correlation would have united them if the facts of present information

had been then available. There could *then* have been little if any reason for assigning these two iron-bearing series to different positions in the Huronian group and there is even less reason for such assignment today, because there is substantial evidence for the correlation of the Ironwood and the Negaunee series on other grounds, which will be discussed below.

CORRELATION OF THE VULCAN (IRON-BEARING) SERIES WITH THE NEGAUNEE (IRON-BEARING) SERIES

Marquette and Crystal Falls districts.—The basis of correlation of the formations of the Marquette and Crystal Falls districts is afforded by an indicated practical continuity of the Negaunee and Vulcan iron-bearing formations. In 1903 H. L. Smyth traced the Negaunee iron formation from the Republic trough southwest around two major anticlines to the northeast side of the great oval anticline in the northern part of the Crystal Falls district.[1] The relation of the Negaunee formation in this area to a persistent magnetic line may be seen on Fig. 3. From the vicinity of Michigamme Mountain, T. 44 N., R. 31 W., where the Negaunee formation is exposed, a magnetic line extends north through the Sholdice and Doan explorations, where the Negaunee is again exposed, and thence, north, northwest, west, and southwest around the great oval anticline into section 27, T. 46 N., R. 33 W., where it still coincides with the position of the iron formation. A short distance beyond the latter locality the line is broken, but it reappears after an interval of about 2 miles and passes through the Red Rock and Hemlock mines at Amasa and beyond, connecting with the iron formation which has been mapped as Vulcan or Upper Huronian.

The United States Geological Survey in 1911[2] accepted the conclusion that the magnetic line, exposures, explorations, and drift bowlders prove the practical continuity of the Negaunee formation from Michigamme Mountain for a distance of 25 miles around the great anticline to a point about a mile south of section 27, T. 46 N., R. 33 W., but from a point about 2 miles farther on,

[1] See Smyth's discussion in *Monograph 36, U.S. Geol. Survey*, pp. 452–55.

[2] *Monograph 52.*

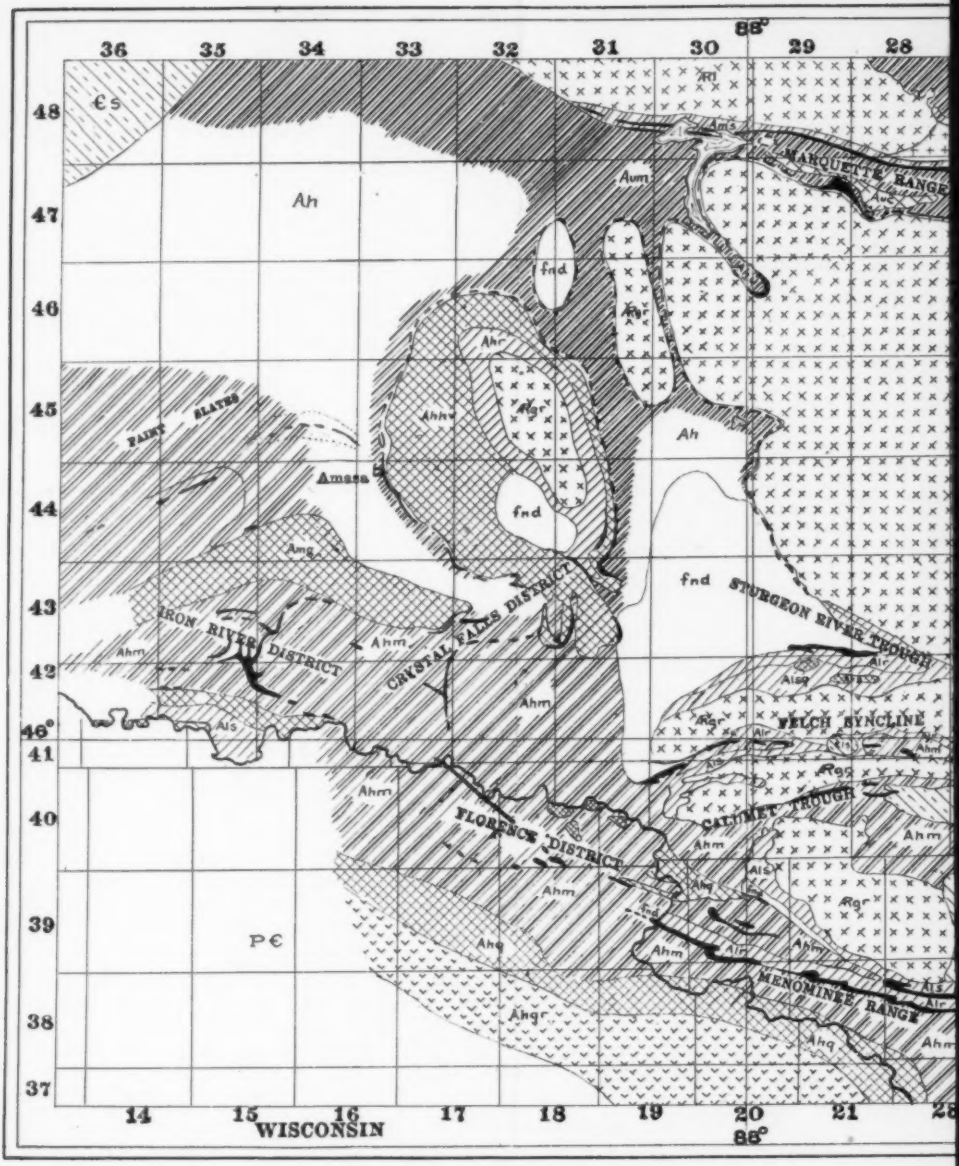
through the Red Rock mine and southward, the iron formation is correlated with the Vulcan or Upper Huronian notwithstanding the facts (1) of similar position with reference to the underlying Hemlock volcanics, (2) that the strike of the magnetic line north of the Red Rock mine indicates a continuity of the Vulcan iron formation there with the Negaunee a little farther north, and (3) that there is no evidence whatever beyond some difference in degree of metamorphism to show that the iron formations in section 27, T. 46 N., R. 33 W., and at the Red Rock mine are not one and the same.

The reason why the iron-bearing series (Vulcan) of the Crystal Falls–Iron River–Florence district was not correlated with the Negaunee by the United States Geological Survey is a simple one. In the Menominee Range, Van Hise and Bayley found that the iron-bearing series is unconformably above a quartzite-dolomite succession similar to the Lower Huronian of the Marquette Range and, under the dual classification, therefore Upper Huronian. Since the Negaunee formation (prior to 1904) had been correlated with the *Lower* Huronian, the question arose as to the position of the iron-bearing series in the intervening districts. It was reasoned that (1) because the iron-bearing series of the Crystal Falls district was at that time inseparable from the great Upper Huronian slate area opening out south and west from the Marquette district, and (2) because the Hanbury slate of the iron-bearing series of the Menominee Range seems to have areal connections with the slates of the Florence–Crystal Falls district, therefore the iron-bearing series in the latter district must be considered Upper Huronian. This conclusion was preferred, notwithstanding the evidence of continuity of the Vulcan and Negaunee formations in the northern part of the Crystal Falls district, and, as we shall see, became a source of considerable difficulty in applying the dual classification to the facts of succession in the Felch Mountain and Florence districts.

Recent developments in the Hemlock and Michigan mines at Amasa have fortunately determined conclusively that the Vulcan iron formation there which had been correlated as Upper Huronian is in reality Negaunee or Middle Huronian. On the thirteenth

level of the Hemlock and Michigan mines the folds in the iron formation are truncated by a heavy conglomerate and quartzite carrying fragments of the Negaunee formation of all sizes up to several feet in diameter, including small, angular, hard jasper fragments, rounded pebbles of chert and ore, and great bowlders of the iron formation. It is reported that this same conglomerate was found by drilling in similar relations to the iron formation about three miles south of Amasa and in section 36, T. 44 N., R. 33 W., about four miles farther southward. There can be no reasonable doubt that this conglomerate-quartzite is the Goodrich formation of the Marquette Range, where exactly similar relations are observed.

The productive iron formation at the Hemlock mine extends with only a few unexplored breaks in drift-covered country southeastward around the great anticline of Hemlock volcanics and other rocks and is believed to be almost if not quite continuous with the iron formation passing through the Hollister, Armenia, and other mines in the vicinity of Crystal Falls. Such continuity is indicated, so far as definite information is available, by drilling, underground openings, and magnetic surveys. Furthermore, the iron formation on the west and southwest sides of the great Crystal Falls oval anticline maintains the same position with reference to the underlying Hemlock volcanics that it does on the north and east sides. Therefore if the iron formation at the Red Rock and Hemlock mines is Negaunee, the burden of proof rests on those who would assert in the absence of any supporting facts that the Upper-Middle Huronian unconformity cuts out the Negaunee iron formation and occupies an inferior position with reference to the Vulcan iron formation at any or all points southward. This practical continuity was accepted by Clements in 1899 and by Leith and Van Hise in 1911, as shown on the maps issued in *Monographs 36* and *52* of the United States Geological Survey. In fact, Leith and Van Hise argue in this work that the iron formation at the Hemlock mine is *not* Negaunee *on the assumption of practical continuity with the Vulcan formation of the Crystal Falls district to the south and lack of continuity with the Negaunee formation a few miles northward.*



GEOLOGIC MAP OF PARTS OF MICHIGAN AND WISCON

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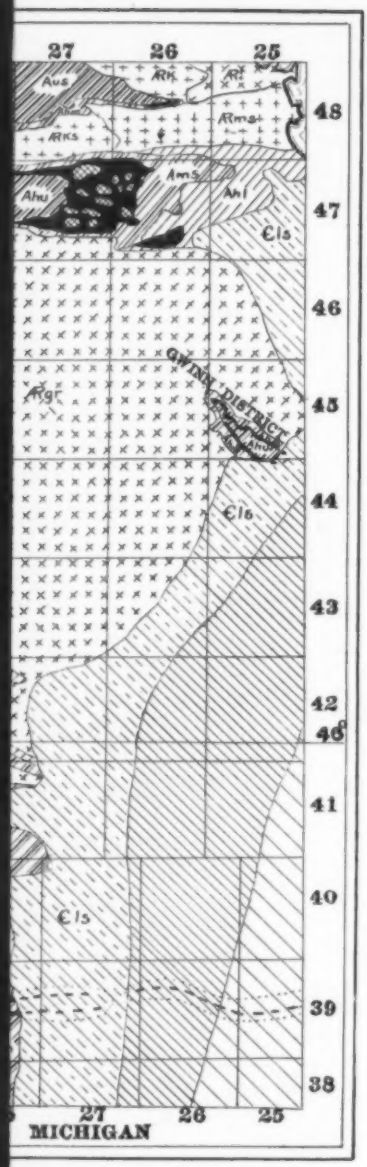

LEGEND

PALEOZOIC

Ordovician

- Middle — Limestones and dolomites
- Lower — White sandstones

Cambrian

- Upper — Lake Superior sandstone

PROTEROZOIC (Algonkian)

Huronian Series

Upper

- Aug – Greenstones
  Auc–Clarksburg Formation
  (Basic Intrusives Acid Eruptives)
- Aum – Michigamme slates
  Aus – Ferruginous slates
  (Quartzites and slates including Iron Bearing Formations)

Middle

- Ahgr – Intrusive Granites
- Ahhv – Hemlock Volcanics
  Amg – Greenstones
  Ahq – Quinnesec Schists
- Ams – Siamo slates
  Amp – Paint slates
  Ahm–Middle Huronian slate
  (Quartzites and slates including Iron Bearing Formations)

Lower

- Alsq – Sturgeon Quartzite
  Als – Saunders Formation
  Alr,Ahr–Randville Dolomite
  (Quartzites, Dolomites, Slates)

ARCHEOZOIC

Archean

- Laurentian — Ægr – Granite
  (Granites and Gneisses)
- Keewatin — Æms – Mona Schists
  Æks – Kitchi Schists
  (Green Schists and Iron Bearing Formations)

- P€ — Undifferentiated Pre Cambrian
- Ah — Undifferentiated Huronian
- fmd — Formation not determinable
- Iron Bearing Formation
- Magnetic Lines

NSIN

10 0 10 20 30 40

SCALE MILES

G. 3

CORRELATION OF THE NEGAUNEE (IRON-BEARING) SERIES WITH THE VULCAN (IRON-BEARING) SERIES OF THE STURGEON TROUGH, FELCH MOUNTAIN DISTRICT, CALUMET TROUGH, AND MENOMINEE RANGE

These ranges lie south of the Marquette district and east of the Iron River–Crystal Falls–Florence district and form eastward-projecting tongues of the Huronian of this great area (see Fig. 3).

1. *Sturgeon River syncline.*—The Negaunee formation has been traced by outcrops, exploration, and magnetic surveys from the Marquette Range into the north limb of the Sturgeon River syncline. From near Witch Lake, about 8 miles south of Republic, the Negaunee formation is shown by the mapping of the United States Geological Survey to rest directly on the Archean. In the Sturgeon syncline, however, the Archean is overlain by the Randville dolomite and Sturgeon quartzite, equivalent to the Kona and Mesnard of the Lower Huronian in the Marquette Range. On the south limb of this syncline the iron formation reappears above the Randville dolomite and has naturally been correlated with the Negaunee of the north limb.

2. *Felch Mountain district.*—The Felch Mountain district is a narrow syncline of Huronian rocks downfolded in the Archean, from one to two miles wide, trending east-west, and, like the Sturgeon trough, opening out westward into the great slate area of the Crystal Falls district, wherein the structure is obscured. It is separated from the Sturgeon trough north of it by an anticline on which the Archean appears as a belt of granite about $2\frac{1}{2}$ to 3 miles wide. In the Felch syncline there is an iron formation (Groveland) similar to that in the Sturgeon trough, separated from the quartzite-dolomite below by conformably underlying sedimentary schist (Felch schist) which has not been observed in the Sturgeon trough, although it may be present there also. Bayley makes no mention of the Negaunee formation of the Sturgeon trough in 1899,[1] although it was subsequently discovered through exploration and is shown on the maps of the United States Geological Survey published in 1911.[2] On these maps the iron formation in the Sturgeon trough is called Negaunee (Middle Huronian) and in the Felch syncline

[1] *Monograph 36, U.S. Geol. Survey.* [2] *Monograph 52.*

Vulcan (Upper Huronian). This seems to be an arbitrary classification and represents the necessity of making the change somewhere from the Negaunee of the Sturgeon trough to the Vulcan of the Menominee Range. Lithologic similarity, proximity, and, so far as known, similarity of succession were cast aside in favor of the supposition that the Felch schist opens out and connects with sediments to the west which had been correlated as Upper Huronian, although the area in which the connection is indicated is deeply drift-covered and devoid of rock exposures. But even if this connection were a fact, as it may be, it constitutes in our opinion merely an added reason why the Groveland iron formation should be correlated with the Negaunee, since the Crystal Falls slate-iron formation series has been shown to be more probably *Middle* rather than Upper Huronian.

As a matter of fact Smyth *did* correlate the Groveland with the Negaunee formation in 1899, but after Seaman's discovery of the unconformity at the base of the Ajibik quartzite necessitated the correlation of the Negaunee series with the *Middle* Huronian (1904), Van Hise and Leith in 1911 took the Groveland out of the *Lower* Huronian and placed it in the *Upper* Huronian. In order to make this change it was necessary to assign a highly metamorphic quartzite-mica schist series which is unconformably *above* the Groveland to the Keweenawan or Paleozoic, for the reason that no place was then left for it in the Huronian group. Smyth was obviously right in correlating the Groveland with the Negaunee formation. The quartzite-mica schist series above the Groveland bears no resemblance to the Keweenawan or Paleozoic. It is Huronian, and we believe it should be correlated with the Copps, part of the Michigamme[1] and the Princeton series. The quartzite which is unconformably above the slate-iron formation series (Animikie) of the Florence district is similarly correlated.

3. *Calumet trough.*—In the Calumet trough, about 4 miles south of the Felch syncline, the situation is practically identical with that in the Felch Mountain district, and the same arguments for revision of the correlation apply here as in the Felch district. In other words, the iron formation now assigned to the Upper

[1] For division of the Michigamme series, see discussion below.

Huronian is believed to be really an equivalent to the Negaunee of the Middle Huronian. Rocks similar to the quartzite-mica schist series of the Felch syncline are exposed at the old Hancock exploration in T. 41 N., R. 27 W., and in at least one or two places near the southern edge of the Calumet trough. Each of the three Huronian series seems to be represented here exactly as in the Felch syncline a few miles north.

4. *Menominee Range.*—The general similarity of the iron-bearing series of the Menominee district with that in the Sturgeon, Felch, and Calumet troughs and in turn with certain phases of the Negaunee formation of the Marquette district, its similarity in relation to the underlying Lower Huronian, and its areal connections with the great slate-iron formation series of the Florence–Crystal Falls district determine that the Vulcan of the Menominee Range is probably of Negaunee age, and that if the iron formation in the districts intermediate between the Menominee and the Marquette ranges is Negaunee there is no basis on lithological, structural, or other grounds for assigning the iron formation of the Menominee Range to any horizon other than Negaunee, i.e., Middle Huronian.

Leith has described a remnant of cherty quartzite, of a maximum thickness of 70 feet, lying apparently unconformably between the Randville dolomite below and the Traders member of the Upper Menominee series above in the vicinity of Norway,[1] but he places no emphasis on it so far as concerns its significance in the correlations. This formation, according to the more recent opinion of Dr. Leith,[2] is a remnant of regolith unremoved by erosion in Lower-Middle Huronian time.

CORRELATION OF THE IRONWOOD SERIES (ANIMIKIE) OF THE GOGEBIC RANGE WITH THE VULCAN (MIDDLE HURONIAN) SERIES OF THE CRYSTAL FALLS–IRON RIVER–FLORENCE–MENOMINEE DISTRICT ON THE BASIS OF SIMILAR RELATIONS TO INTRUSIVE GRANITE

Area southeast of the Gogebic Range including Marenisco, Turtle, Manitowish, Vieux Desert, Conover, Iron River, Crystal Falls, and Menominee districts.—Probably the most striking feature of the

[1] *Monograph 52, U.S. Geol. Survey*, pp. 234–35.

[2] As expressed in conversation with the writer.

Middle Huronian (Animikie) of these districts is the general prevalence of intrusive granite. Heretofore these granites have been variously correlated, from Laurentian in the Gogebic, northern Wisconsin, and Menominee districts through the Upper Huronian in the Crystal Falls district to Keweenawan in the Florence-Menominee and northeastern Wisconsin areas.

In the Menominee district Bayley found that the granite south of the Menominee River intrudes a series of basic volcanics called the Quinnesec schist, which he correlated with the Keewatin. Although it was realized that the correlation of the Quinnesec schist as Keewatin introduced a conception of structure quite out of accord with natural inferences on the basis of the facts, it remained for Corey and Bowen, working under the direction of Van Hise and Leith in 1905,[1] and Hotchkiss in 1910,[2] to show conclusively that the Quinnesec schist is partly intrusive into, but in greater part interbedded with, the upper part of the Upper Huronian, i.e., Animikie.[3]

Inasmuch as the granite was thus proven to be the youngest rock in these districts, and the youngest pre-Cambrian sediments had been correlated with the *Upper* Huronian, Leith and Van Hise in 1911[4] correlated the granite with the Keweenawan and extended the boundaries south and east to include several thousand square miles of acid intrusives in north-central Wisconsin which had been mapped and described by Weidman in 1905.[5]

It is interesting to note here that Brooks and Wright had correctly interpreted these relations as early as 1876, although they did not, at that time at least, comprehend the extent of the great mass of intrusive granite. To quote from Brooks:

> In the summer of 1874 Chas. E. Wright and myself, exploring the country west and south of the Menominee River about 90 miles from its mouth, under the auspices of the Wisconsin Geological Survey, observed a large granite

[1] Unpublished notes of field work done in 1905 by G. W. Corey and C. F. Bowen.

[2] Unpublished field notes of W. O. Hotchkiss.

[3] Middle Huronian of this article.

[4] *Monograph 52, U.S. Geol. Survey.*

[5] S. Weidman, "The Geology of North Central Wisconsin," *Bull. Wis. Geol. and Nat. Hist. Survey*, No. 16, 1907.

area, the north edge of which was bounded by dark colored hornblendic and micaceous schists of Huronian age, which I have since concluded are equivalents of the youngest member of that series yet observed in the Marquette iron region. . . . . The lithologic character of this wide granite belt bore so much resemblance to the Laurentian rocks, which are extensively developed on the waters of the Sturgeon River in Michigan, 10 to 20 miles to the northeast, that we were disposed at the time to believe that some phenomena of folding or faulting had brought rocks belonging to that system to the surface in an unexpected quarter. Professor Pumpelly and myself, several years previously, had observed, farther to the north and west, similar granitic rocks crossing the Michigamme and Paint rivers (branches of the Menominee), presenting similar puzzling relations with beds known to be Huronian, and younger than as well as lithologically different from any rock then known to be of that period.

A careful consideration of all of the facts to be observed in the Menominee region confirms me in this hypothesis. . . . .[1]

The conclusion of Brooks is confirmed by the work of Hotchkiss in the Florence district of Wisconsin in 1910.[2]

In 1911–14 the writer and assistants, through field mapping and diamond drilling, traced what appears to be this same granite from the Iron River district westward through the Animikie series of the Vieux Desert–Conover district and Manitowish, Turtle, and Marenisco ranges, in all of which it is in intrusive relation with the sediments, and connected it with the "Eastern Laurentian area" of Van Hise and Irving on the eastern Gogebic Range, which was considered by these geologists to form a part of the Archean basement complex, whereas it actually intrudes the Lower and Middle Huronian series and is unconformably overlain only by the Upper Huronian (Copps) series. *Thus the great granite batholith of northern Wisconsin has been fairly demonstrated to be, not only in intrusive relations with the Animikie sediments over several thousands of square miles, but also to be overlain unconformably by a pre-Cambrian series which is unconformably below the Keweenawan.*

Inasmuch as the Vulcan (Animikie) series of the Crystal Falls, Iron River, Menominee, Florence, and other Michigan districts has been shown to be very probably equivalent to the Negaunee

[1] T. B. Brooks, "On the Youngest Huronian Rocks South of Lake Superior and the Age of the Copper Bearing Series," *Am. Jour. Sci.*, Vol. II (1876), 206–7.

[2] Unpublished manuscript.

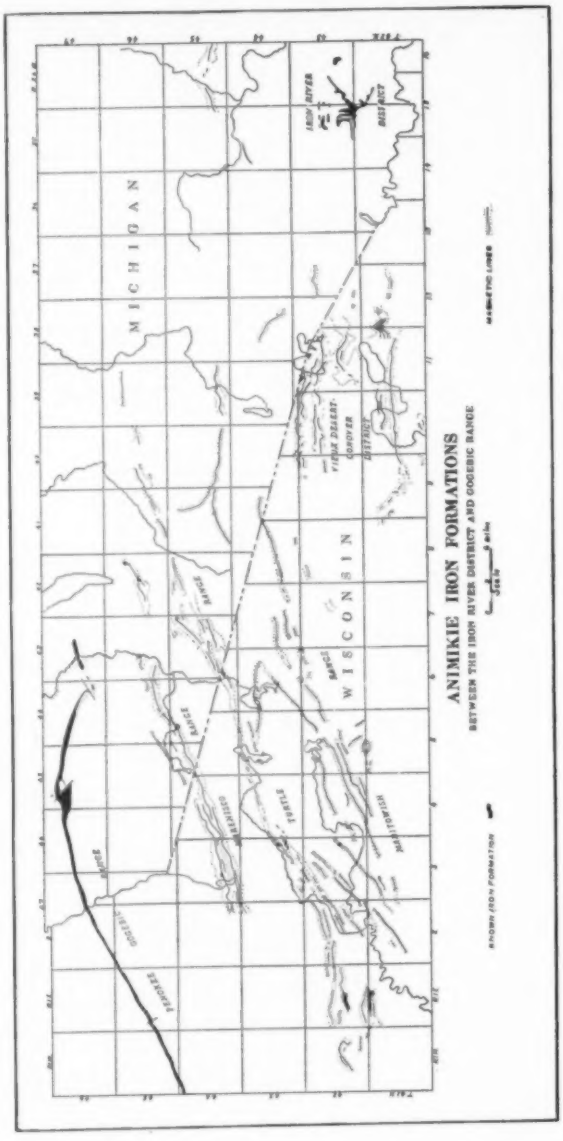
MICHIGAN
WISCONSIN
ANIMIKIE IRON FORMATIONS
BETWEEN THE IRON RIVER DISTRICT AND GOGEBIC RANGE
KNOWN IRON FORMATION
MAGNETIC LINES
IRON RIVER DISTRICT
FLORA DESERT-GROVER DISTRICT
BARCO
MENOMINEE
FOURTEEN
PENOKEE
BOUNDARY

FIG. 4

series of the Marquette Range and the Ironwood series of the Gogebic Range, the age of this great granite batholith and its outliers may be considered as late Middle Huronian.

CONSIDERATION OF ARGUMENTS WHICH MAY BE ADVANCED FOR THE RETENTION OF THE CORRELATION OF THE ANIMIKIE AS UPPER HURONIAN

We have seen that the correlation of the Animikie as Upper Huronian dates from the earliest work of the United States Geological Survey in the Lake Superior region. It seems reasonable to believe that if the early workers in the Gogebic and Marquette ranges had recognized that the Huronian of both exhibits a *tripartite* rather than a dual division, the Animikie would have been considered by them as Middle Huronian rather than Upper Huronian. We have referred to some of the difficulties which were encountered in the application of the dual classification to some of the other Michigan ranges and have shown how these difficulties largely disappear in the correlation of the Animikie series as Middle Huronian. Having established the basis of the proposed correlation, we may turn to a consideration of some of the objections which may be offered to it.

Dr. Leith has emphasized the general similarity of the slate in the great Iron River–Crystal Falls area and the Animikie slates of the Cuyuna and Mesabi districts of Minnesota, and believes that "there is probably but one great slate formation of *this type* in the Lake Superior region." Although this observation has little bearing on the question of whether the Animikie is Middle or is Upper Huronian, it may be observed that this similarity is marked so far as concerns the slates which occur in areal association with the iron formation, but does not extend to the great mass of slate which occupies a large area of indefinite boundaries north and west of the Crystal Falls–Iron River iron-bearing area. These rocks are mainly graywacke of uniform composition and appearance and are not at all similar to the fine-grained gray and black pelites of the Animikie series which are associated with the iron formation (Vulcan) in the Iron River, Crystal Falls, Florence, and Menominee districts and the Negaunee iron formation of the Marquette Range.

The contrast is so marked that in 1910 I described these graywackes under the distinct formation name[1] of Paint slate and called attention to the structural evidence indicating that they are stratigraphically *above* the Vulcan (Animikie) series.

The correlation of the Paint formation presents a difficult problem. It constitutes a large part of the Michigamme series heretofore correlated with the Upper Huronian. We have seen that there is strong evidence that the Vulcan slate-iron formation series of the Iron River–Crystal Falls district, which has been described as a part of the Michigamme, is Middle Huronian. That part of the Michigamme slate which is *known* to be Upper Huronian is confined to a limited area adjacent to the western part of the Marquette iron range and the northern part of the Crystal Falls district where it is plainly unconformably above the Negaunee iron-bearing series. If the Paint slate is *conformable* with the Negaunee-Vulcan, it follows that the part of the Michigamme slate which is Upper Huronian must rest unconformably on it, and from the areal distribution of these formations it appears that the plane of the unconformity should intersect the erosion surface somewhere *north* of the Paint formation north of the Iron River district. Unfortunately, a general scarcity of exposures in the area where the unconformity may be expected to occur and the difficulty of identifying horizons over any considerable distance in formations of these kinds will render the discovery and mapping of this unconformity, if it exists, difficult. It is being searched for at the present time.

As bearing on the probable age of the Paint formation it may be said here that the Wolf Lake granite, north of Watersmeet in T. 46 N., R. 39 W., is intrusive in quartz-mica schist which, judging from lithology and areal relationships, is a metamorphic equivalent of the Paint slate. The Wolf Lake granite is correlated with the Presque Isle granite of the Gogebic Range and that in the intervening territory and is believed to be an outlier of the great granite batholith of northern Wisconsin. The Presque Isle granite intrudes the *Middle* Huronian (Animikie) and yields detritus to the Upper

[1] R. C. Allen, "The Iron River Iron Bearing District of Michigan," *Publ. 3, Mich. Geol. and Biol. Survey*, 1910.

Huronian. If the Presque Isle and Wolf Lake granites are of the same age, it follows that the Paint formation is Middle Huronian.[1]

In the argument for retention of present correlations which follows, Dr. Leith is unable to accept the correlation of the Vulcan series of the Crystal Falls–Iron River district with the Negaunee series of the Marquette Range, for the reason, among others, that the Vulcan iron formation occurs in lenses in slate, as against the well-defined position of the Negaunee formation in the stratigraphic succession. In this connection it should be observed that this dissimilarity of occurrence is fully as great and of the same order in comparison with the Animikie series of the Gogebic, Mesabi, and old Menominee ranges with which the Vulcan is correlated by him as well as by me. If the observation is of importance in the one case, is it not equally so in the others?

In further reference to the correlation of the Negaunee and Vulcan iron-bearing series, it may be observed that the Negaunee series in the Marquette trough is thick and well developed and should be expected to occur in the down folds over a large area. The Ajibik quartzite has a maximum thickness of 700–750 feet, the Siamo slate probably from 500–600 feet, and the Negaunee iron formation in excess of 1,000 feet. The Siamo slate is not persistent on the south side of the trough west of the latitude of Ishpeming, where the Negaunee rests directly on the Ajibik quartzite. The Negaunee formation, as well as the underlying quartzite, becomes thinner in this direction, and in the Sturgeon trough and around the great anticline in the Crystal Falls district the Ajibik formation, according to the latest maps of the United States Geological Survey (1911), is entirely absent, the Negaunee formation there resting directly on the Lower Huronian. The correlation of the Vulcan formation of the Crystal Falls district with the Negaunee formation of the Marquette district is criticized by Dr. Leith on the basis of the apparent absence of the Ajibik quartzite in the former area. However, *the Ajibik formation is known to have disappeared from beneath the Negaunee in the direction of the Crystal*

[1] R. C. Allen and L. P. Barrett, "Contributions to the Pre-Cambrian Geology of Michigan and Northern Wisconsin," *Publ. 18, Mich. Geol. and Biol. Survey* (in press).

Falls district, as indicated on the latest maps of this district published by the United States Geological Survey.

As to the importance which may be attached to the absence, in the southern part of the Crystal Falls district, of the formations which underlie the Ajibik quartzite adjacent to the iron formation in the Marquette Range, it may be observed that these formations appear not only on the great anticline in the northern part of the Crystal Falls district but on the upturned limbs of the synclines to the east—the "eastward-projecting tongues of this great area," wherein erosion has cut down into the Archean.

Finally, it may be said that it is easier to account for the disappearance of a coarse clastic basal member which is obviously related to a shore phase of deposition than to justify, in the absence of definite supporting facts, the assumption of a rather abrupt disappearance of an entire series.

It may be objected further to the correlation of the Vulcan and Negaunee formations that the hard ore horizon of the upper part of the Negaunee is not duplicated in the Vulcan of the Crystal Falls district. This fact has little bearing on the correlation because this phase of the Negaunee is related, as shown by Van Hise and others, to a controlling structural condition which nowhere occurs in the Crystal Falls district, i.e., it is the result of deformational-metamorphic alteration adjacent to the heavy competent Goodrich quartzite-conglomerate. This relationship, areally considered, is entirely fortuitous and may be expected to appear only where the structural conditions and deformation on which it is dependent are in evidence. So far as *lithology* is concerned the Vulcan and Negaunee formations are in other respects practically identical.

Dr. Leith opens his discussion of the Upper-Middle Huronian unconformity at the Hemlock mine and vicinity as follows: "Practically no new evidence has been brought in, in the crucial area between the Marquette and Crystal Falls districts, and such additional evidence as there is, is damaging to the conception of the new hypothesis." The discovery of that unconformity has apparently reversed Dr. Leith's ideas concerning the correlation of the iron formation in the northern part of the Crystal Falls district which he recently (1911) correlated with the Vulcan but

now correlates with the Negaunee and refers to it as "distinctively Negaunee type." If the Hemlock iron formation and the Vulcan were considered the same in 1911 and prior years, what *new evidence* may be cited on which they may be separated *now?* The only *new evidence* is the discovery of the fact that the iron formation at the Hemlock mine and for several miles north and south of it is Negaunee, and this is therefore precisely the evidence to which Dr. Leith refers as damaging to the new hypothesis and in confirmation of the old correlation.

Dr. Leith has also laid emphasis on the fact that the unconformity at the Hemlock mine has not been traced across the northern part of the Iron River district and therefore that proof is lacking that any part of the Michigamme slate occupies an inferior position with reference to this unconformity. This is a weakness in the new hypothesis, but it is certainly not greater than the weakness in the argument which has been advanced that this unconformity cuts out the Negaunee formation in the northern part of the Crystal Falls district and in some unknown place passes beneath the Vulcan formation of the southern part of the district. If the greenstone belt north of the Iron River district is Hemlock (Middle Huronian) as correlated by Clements as well as by Van Hise and Leith (1911), there is an anticlinal structure here which *demands* that the unconformity turn "back on itself at some place south of Amasa" and carry "out westward to the north of the Iron River–Crystal Falls district" (see Fig. 3). This would seem a necessary consequence of Dr. Leith's published interpretation of the structure with which I agree (in reversal of my opinion in 1909) because of the discovery of the unconformity in question and the evidence based on the recent drilling in the vicinity of Crystal Falls. In brief, the structural facts point to a closely compressed syncline between the two masses of volcanics, similar to those northeastward including the Republic trough, with the formations involved sharply upturned on its opposite limbs.

GENERAL REMARKS ON THE CORRELATION OF THE ANIMIKIE SERIES WITH THE MIDDLE HURONIAN

The correlation of the Animikie series with the Middle Huronian eliminates what would otherwise be the necessity of assuming a

fourth Huronian series of which the Copps formation of the Gogebic Range would be the sole representative. The practical identity of the Huronian succession of the Gogebic and Marquette ranges, together with the marked similarity of the Copps formation and the Upper Huronian of the Marquette and Gwinn districts, is believed to be an adequate basis for moving the Animikie of the Michigan and other Huronian districts downward into the Middle Huronian, particularly as this correlation, as we have seen, eliminates what would otherwise be a further necessity of including the uppermost series of metamorphic sediments in the Felch, Calumet, and Florence districts in the Keweenawan or the Paleozoic, where they obviously do not belong.

The anomalous position in the correlations of the great Negaunee iron-bearing series has been unsatisfactory to many students of the pre-Cambrian for many years.[1] We now have a firm basis for the correlation of the Negaunee series with the great productive iron-bearing series of the Animikie of all of the other districts of the Lake Superior region and are able to recognize the consideration that the unique conditions which resulted in the deposition of the great Huronian iron formations were regional rather than local and should be correlated in time. While it is true that the names now used have come to have well-understood significance because of long usage, it cannot be held that this is a valid argument for the retention of a classification which no longer fairly interprets the facts of present knowledge.

ARGUMENTS FOR RETAINING THE PRESENT CORRELATION

C. K. LEITH

Doubts as to the present correlation of the Michigan formations center in the great slate area (Michigamme slate) carrying the iron formation of the Iron River, Crystal Falls, Florence, and con-

[1] See A. C. Lane and A. E. Seaman, *Mich. Geol. Survey, Annual Report*, 1908, pp. 23–30. In presenting their mature conclusions on Michigan pre-Cambrian sucessions, Lane and Seamen correlate the Animikie iron-bearing series throughout with Negaunee (Middle Huronian) of the Marquette Range.

tiguous districts, which lies between the well-determined succession of the Gogebic on the one hand and the well-determined succession of the Marquette on the other. The close folding of this area, its intrusion by granite, its relatively soft character, causing low relief and few exposures, the fact that exploration and development in this area are much less advanced than in the Gogebic and Marquette districts, the fact that there is a general absence of distinctive quartzite or other formations as horizon-markers, have made it difficult to carry correlations with certainty through this great slate area. In general, the slates show evidence of shallow water or delta deposition in their rapidly alternating bedding, current bedding, ripple marks, graphitic layers, and considerable thickness. In all these respects it differs from any of the slates, other than Animikie, in the pre-Cambrian of Lake Superior. It is substantially like the slate above the Animikie iron formation of the Gogebic and Mesabi districts, like the Animikie of the Cuyuna and St. Louis River districts, and like the Michigamme slate of the Upper Marquette series (Animikie). Throughout the great slate areas of this type in the Lake Superior region the iron formation has somewhat similar characteristics, being in irregular folded, more or less discontinuous, lens-like bands within the slates, without definitely determinable horizon. The occurrence and nature of the ores are so much alike throughout these great slate areas that they are naturally grouped by the explorers or mining men.

Nearly all investigators of the geology have noted these broad similarities and have correlated the slates of these districts as Animikie.

In arguing for the revision of pre-Cambrian correlation of Michigan, Allen accepts the correlation of the slate series of the Iron River–Crystal Falls district with the Animikie or Upper Huronian of the Gogebic district, but its correlation with the Upper Huronian or Animikie of the Marquette district is disputed on the ground that it may be the equivalent to the Middle Huronian of the Marquette district, leaving the Upper Huronian of the Marquette district available for correlation with the newly discovered Copps series. The discovery of this new series leads, naturally, to a search for a more extensive occurrence in the region, but, in my

judgment, the proposed change runs squarely across certain fundamental facts which will not give way to the new hypothesis, however attractive it may be. Allen's argument is based (1) on the supposed equivalence of the Iron River slates (and iron formation) with the Animikie in the Gogebic district, (2) on the supposed equivalence of the Iron River slates with the Middle Huronian of the Marquette district.

1. That the slates and iron formation of the Iron River district are to be correlated with the Animikie of the Gogebic district is the conclusion that has been reached by nearly all investigators, and in the absence of definite proof to the contrary must stand. I would suggest, however, that the recent discovery of the Copps series opens up an alternative, that the Iron River series is equivalent to the new Copps series and both equivalent to the Upper Huronian of the Marquette district. This would have the effect of throwing the Animikie down a step in the scale, but would not disturb the local correlation between the Marquette and Crystal Falls–Iron River districts. This is only a possibility, for outcrops are few in the connecting areas, metamorphism due to intrusion has been intense, and I see no likelihood for some years of sufficient information being available to develop the evidence necessary for this possible conclusion.

2. That the slates and iron formation of the Iron River–Crystal Falls district are equivalent to the Negaunee (Middle Huronian) of the Marquette district is a possibility which has been often considered discarded. Practically no new evidence has been brought up in the crucial area between the Iron River–Crystal Falls district and the Marquette district, and such additional evidence as there is, is damaging to the conception of the new hypothesis.

The great essential fact of the situation, which cannot be ignored, is that in the Marquette district the Negaunee iron formation (Middle Huronian) is unconformably below a great slate series (Michigamme slates, Upper Huronian) which contains lenses of iron formation identically like those in the Crystal Falls and Iron River districts, and contrasting with the Negaunee iron formation of the Negaunee. The Michigamme slate of the Marquette district is all but proved to be the same as that in the Iron River and Crystal

Falls region. They are areally contiguous, contain the same lithologic types, and throughout contain iron formation of remarkably uniform type and occurrence. To assume that they are not of the same age requires not only the introduction of an entirely hypothetical unconformity, but also the assumption that the Negaunee formation has entirely changed its character to the exact extent necessary to make it similar to the slate-iron formation of the Crystal Falls–Iron River district. Such a thing is of course possible, but extremely improbable.

Nowhere in the Crystal Falls–Iron River district has the close folding and erosion disclosed the distinctive Siamo slates of the underlying Ajibik quartzite characteristic of the horizons below the Negaunee. Neither has it disclosed any formations underlying the Ajibik close at hand, with the exception of certain volcanics. Somewhere they should appear on the erosion surface if the series were really Middle Huronian.

That there are two slates in the Iron River–Crystal Falls district, as argued by Allen, is possible, but no trace whatever of an unconformity has been found, and the differences in lithology which he cites as evidence are completely duplicated by differences in lithology in the Upper Huronian slates of the Marquette district.

The principal argument for a change in correlation is based on a supposed direct areal connection of the Negaunee iron formation of the Marquette district with the iron formation of the Iron River–Crystal Falls district. With some interruption, due to folding, the Negaunee iron formation has been traced southwestward from the Marquette district to a point in the northeast portion of the Crystal Falls district near Amasa, on the west side of an area of underlying Hemlock volcanics. Somewhere south of this area the character of the iron formation changes, for before reaching the iron formation belts in the slates (Upper Huronian) in the vicinity of Crystal Falls, the formation is of different character, the underlying fragmental phases are absent, and both walls are conformable slate. The difficulty of drawing a line here, in the absence of exposures and complete exploration, has long been obvious, and yet the contrast in types and occurrence of iron formation seem to require that some line be drawn. In successive maps the line has shifted more or less.

The general accuracy of the conclusion that the two formations are of different age has been strengthened by the finding of a basal conglomerate resting directly on the Negaunee formation and locally cutting it out in the general vicinity of Amasa. So far as this conglomerate has been traced (6 or 8 miles) it shows conclusively that the slate series on the west is unconformably above the Negaunee formation on the east. Where this unconformity goes to the south is not yet discovered, and hence there is still doubt as to the exact location of the line of contact between the Negaunee iron formation and the Upper Huronian. The extension of the unconformity along its trend south or southeast in general separates the formation of distinctly Negaunee type on the east from the formation of distinctly Iron River–Crystal Falls type associated with slates on the west. Allen, on the other hand, would turn the unconformity back on itself at some place south of Amasa and carry it out westward to the north of the Iron River–Crystal Falls district, in order to leave the Iron River–Crystal Falls iron formation with the Negaunee formation below the unconformity. It seems possible that the unconformity to the south of Amasa cuts out the Negaunee formation, allowing the Upper or Animikie series to lap over against the underlying formation, exactly as happens in places in the Marquette district. The statement that the known Negaunee formation is areally connected with the known Crystal Falls–Iron River iron formation is based on general similarity of trend of the iron formation, as shown by explorations and various magnetic belts. As the two have been folded together, this similarity of trend is to be expected in any case. There is plenty of room for the unconformity to run diagonally across this general trend at almost any point. Exactly the same argument for connection in the Marquette district would result in mapping Negaunee iron formation with Upper Huronian iron formation, whereas the two are really separated by a profound unconformity.

The writer is not impressed with the argument that if a threefold division of the Huronian had been first made, subsequent correlation would have been of a different sort. It is entirely true that different correlations might result in starting from a twofold or threefold basis of division, but the history of correlation of pre-

Cambrian formations in the Lake Superior country discloses no backwardness in revising correlations as fast as facts are found to warrant revision. Seaman's discovery of a tripartite division in the Marquette district was immediately recognized by the geologists of the United States Geological Survey and was first published by C. K. Leith in 1904,[1] with permission of Professor Seaman. Neither may it be said that there is any delay in recognizing the significance of the supposed new formation in the eastern Gogebic district. In fact, the writer took some part in the field in the analysis of the situation leading up to this discovery. It may be freely conceded that in the past there was more emphasis on a given number of series as a basis of correlation, but the basis of correlation has been constantly widened by the addition of new criteria. It seems peculiarly inappropriate, therefore, to argue that what might have been done in the past on the basis of a preconceived notion of a number of series should serve as a primary basis of classification now when a much greater variety of facts is available.

In short, the suggested changes in correlation seem to the writer interesting possibilities, for which evidence must be carefully looked for in further geological work in this district, but that they are only possibilities and in the present state of knowledge cannot stand against the general considerations above outlined. It should not be overlooked that the new series suggesting these sweeping changes is yet known in but a few outcrops in a limited area where the folding and intrusion have been extensive, and that there is distinct possibility that the formation may have been of only local significance.

In case the newly proposed classification can be established it will be a welcome advance in our knowledge of Lake Superior geology. The purpose of this argument is not to discourage an attempt to make such an advance, but to indicate the difficulties inherent in the problem and the impossibility in the present state of knowledge of accepting an interesting hypothesis as a proved fact.

[1] C. K. Leith, *Trans. Am. Inst. Min. Engrs.*, Lake Superior meeting, 1904.

PRESSURE AS A FACTOR IN THE FORMATION OF ROCKS AND MINERALS

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It is not surprising that application of the knowledge comprised in the older chemistry should have yielded comparatively little information as to the way in which rocks and minerals actually form; and for this reason. The older chemistry dealt in the main with the formation and behavior of substances at temperatures confined to a very small range and practically at a single pressure only—that of the atmosphere; in other words, it dealt with the merest slice of the surface which would represent the behavior of the substance throughout the range of temperature and pressure within which it is capable of existence. At the same time there was a failure to recognize that its work was so limited in character, and consequently the endeavor to deduce regularities from the behavior of substances at ordinary temperature and pressure—under arbitrary conditions, in other words—was but partially successful. The reason for this is clear if we consider how our ordinary chemistry—that of the 20° C. level—would be changed at the 200° level, for a large number of compounds would then have become unstable; and again, that the number of compounds persisting at the 1,000° level, and a fortiori at the 2,000° level, would be but a small fraction of those which exist at ordinary temperatures.

Igneous rocks and minerals have formed under conditions much removed from 20° and 1 atm. pressure; so that we are little likely to ascertain much about their formation except by thorough and extensive investigations over a wide range of temperatures and pressures, investigations which would at the same time throw much needed light on a number of very important chemical problems. Incidentally it may be observed that the variables temperature and pressure are completely analogous; that besides the ordinary freezing-point of a liquid—in stating which we imply a definite

pressure of 1 atm.—there is also the freezing-pressure at a definite temperature; for example, mercury freezes at $-38.85°$ under 1 atm.; at 0° C. its freezing-pressure—the pressure which will cause it to freeze—is about 7,600 atm.

The purpose of the present paper is to discuss briefly the available experimental evidence in the light of the principles involved, to indicate the conclusions which the somewhat scanty observations seem to justify, and to point out the limitations to which such conclusions are necessarily subject. In general it would seem that the importance to geology of the effects of pressure upon changes such as the melting of a single pure substance—those, namely, usually regarded as physical changes—has been overestimated relatively to that of the influence of pressure upon systems containing more than one component—namely, upon chemical changes. The influence of pressure upon chemical equilibrium is especially marked if one or more of the components of the system are volatile, and must therefore be taken into account in any discussion of the behavior of the magma; indeed, the order of separation from a complex solution containing a volatile component depends just as much on whether, and how, the pressure changes as upon the mode and rate of cooling.

There has been very little direct experiment on the influence of pressure upon the formation of rocks and minerals, by reason of the technical difficulties in the way of making such experiments; so that we are forced in large part to reason from analogy with those substances whose behavior it has been possible to investigate. In reasoning from analogy we must, of course, bear in mind the inherent limitations to which conclusions thus derived are subject. On the other hand, in reasoning backward from present-day field evidence, one must also proceed with caution; for, presuming even that one is aware of all the factors in the net result as we see it, it is hard to disentangle the effects of these several factors, especially since the intensity of each is in general unknown. For example, we can make only a very rough guess at the temperature and pressure prevailing at the time when a given process was taking place, and consequently cannot gauge satisfactorily the relative importance of these factors in producing the result as we see it. Moreover, the

composition of a rock mass as we see it now is no absolute criterion of what was the total composition of the magmatic solution from which it separated; for we are ignorant of the character and amount of the volatile components which were present in the original liquid magma.

In discussing metamorphic processes—or indeed in any discussion of the effects producible by pressure—one must remember to distinguish carefully between uniform (or pure hydrostatic) pressure and non-uniform compression, which is equivalent to a stress; for the former is incompetent to produce some of the results which may be brought about by the latter. This distinction is important; failure to observe it has led to many apparently contradictory statements, and consequently to some confusion. The main difference is that whereas a homogeneous solid body recovers its original dimensions and properties when relieved from a uniform pressure, it is changed permanently by a stress, provided that the stress exceeds the elastic limit of the solid; this residual effect is evident as a change of shape—a deformation—which is accompanied by a change in several other properties, e.g., in the case of metals by changes in density, electric resistance, and thermoelectric power. That the effects of stress on a crystalline aggregate outweigh those of uniform pressure follows from thermodynamical principles if we identify a deformation under stress with a real, partial, local temporary melting, on the basis that the stress acts upon the solid but not upon the liquid phase.[1] This hypothesis, which is not in conflict with any direct experimental evidence, serves to correlate a number of observations on the flow of rocks and of metals, and has in recent years been utilized by several English metallographers as a means of accounting for phenomena connected with the important question of the hardening of metals. In this connection it may be pointed out that the circumstance that a solid has been deformed indicates, not that its strength was necessarily small, but that the shearing forces to which it was exposed were great enough to overcome the resistance to deformation offered by the solid; in other

[1] This hypothesis, and some of its consequences, have been discussed in previous papers; see Johnston and Adams, *Am. Jour. Sci.*, XXXV (1913), 206; Johnston and Niggli, *Jour. Geol.*, XXI (1913), 599.

words, the fact that a rock has flowed is no criterion of its strength, nor does it indicate that at the time of flow the rock was necessarily liquid as a whole.

Let us now consider briefly the effects of uniform pressure upon some of the properties of a pure crystalline substance, taking up first its melting-curve. For a pure crystalline substance there is, at a definite pressure, a single temperature—the melting-point—at which its solid and liquid forms can coexist indefinitely in equilibrium, this being the temperature at which the vapor pressure of solid and that of the liquid become identical. The melting-point is influenced by change of uniform pressure—such as we may conceive to be exerted by either a gas or a mobile liquid (e.g., oil) which is insoluble in the substance. By joining up the melting-points at various pressures we obtain the melting-curve, the slope of which (dT/dP) at any point can easily be shown to be

$$\frac{dT}{dP}=\frac{T\Delta V}{\Delta H}$$

where T, ΔV, and ΔH are respectively the melting-point, the change of volume, and the heat change (latent heat of fusion) at that particular point on the curve. From this equation it is obvious that the general shape of the curve is determined by the way in which ΔV and ΔH vary with the pressure; that the condition for a maximum melting-point is that ΔV should vanish while ΔH remains finite, and for a critical end-point solid-liquid that ΔV and ΔH should vanish simultaneously. But we cannot predict from theoretical principles how ΔH and ΔV will vary—in other words, the shape of the curve can be determined only by experiment. In this connection it may be noted that there is no general relation between ΔH and ΔV, for we may have a large latent heat associated with a small volume change and vice versa; indeed, in two particular cases we have a negative volume change with a positive heat effect, these two exceptional cases—ice I and bismuth—being the only pure substances whose melting-point is known to be lowered by pressure. There is little doubt that the silicates are normal in this respect, showing a rise of melting-point with increase of uniform pressure, because everything indicates that they expand on melting

—that at the melting-point the volume of the liquid is greater than that of the solid.

The best and most extensive experimental work is that of Bridgman,[1] who determined the melting-curve of a number of substances at pressures up to 12,000 atm.—a pressure corresponding to a depth below the surface of the earth of about 30 miles. Some of his data are presented in Table I, which shows especially the gradual diminution of the effect with each successive pressure increment. Bridgman also made direct measurements of the change of volume on melting (ΔV) throughout his pressure range, and found that it decreases slowly and at a continuously decreasing rate; the shape of the curve suggests that the change of volume would not become zero at any finite pressure. Moreover, by combining his data and using the foregoing equation he calculated ΔH; it does not tend toward zero at higher pressures, but remains approximately constant, showing if anything a tendency to increase with the pressure. The general conclusion from this work accordingly is that, up to pressures of 12,000 atm. at least, there is no indication of a maximum melting-point, still less of a critical end-point solid-liquid; on the contrary everything indicates that such points, if indeed they exist at all, can occur only at pressures altogether outside the range of possible experiment at the present time.

Table I illustrates another interesting point: namely, that at a pressure of about 5,800 atm. the melting-point of solid CO_2 has reached 31°, the critical temperature of the liquid; at pressures higher than this it sublimes or passes directly into a gas. Consequently it is in this case actually possible to pass directly from a *gas* (not a vapor, for it is above the critical temperature) to crystalline solid merely by change of pressure. This would indicate that application of sufficient pressure would convert even a gas into a solid, and suggests that the existence of any large body of gas deep in the earth is as little likely as the existence of much liquid.

All of this evidence then tends to corroborate the belief that the central portion of the earth is substantially solid, though this does not imply that this solid will not flow whenever opportunity

[1] P. W. Bridgman, *Proc. Am. Acad.*, XLVII (1911–12), 347; *ibid.*, XLVII (1911–12), 439; *Physic. Rev.*, III (1914), 126, 153.

occurs for it to do so, since the stresses to which it is exposed must be far in excess of its elastic limit, even at moderate depths.

TABLE I

MELTING-CURVES OF VARIOUS SUBSTANCES (AFTER BRIDGMAN)

PRESSURE KG. PER SQ. CM.*	MERCURY		POTASSIUM		SODIUM		NITROBENZOL		CARBON DIOXIDE	
P	*t*	Δ*t*	*t*	Δ*t*	*t*	Δ*t*	*t*	Δ*t*	*t*	Δ*t*
1	−38.85		62.5		97.6		5.6		−56.6	
		5.10		16.2		8.6		21.9		19.3
1,000	−33.75		78.7		106.2		27.5		−37.3	
		5.09		13.7		8.1		21.2		16.8
2,000	−28.66		92.4		114.3		48.7		−20.5	
		5.09		12.3		7.6		19.9		15.2
3,000	−23.57		104.7		121.9		68.6		− 5.3	
		5.09		11.1		7.2		18.8		13.8
4,000	−18.48		115.8		129.1		87.4		+ 8.5	
		5.08		10.2		6.9		17.7		12.7
5,000	−13.40		126.0		136.0		105.1		21.2	
		5.08		9.4		6.6		16.9		11.7
6,000	− 8.32		135.4		142.6		122.0		32.9	
		5.07		8.7		6.3		16.1		11.1
7,000	− 3.25		144.1		148.9		138.1		44.0	
		5.06		8.1		6.1		15.5		10.6
8,000	+ 1.81		152.2		155.0		153.6		54.6	
		5.06		7.5		5.9		15.1		10.2
9,000	6.87		159.7		160.9		168.7		64.8	
		5.05		7.0		5.7		14.8		9.9
10,000	11.92		166.7		166.6		183.5		74.7	
		5.04		6.6		5.4		14.5		9.6
11,000	16.96		173.3		172.0		198.0		84.3	
		5.03		6.2		5.2		.....		9.3
12,000	21.99		179.5		177.2		.....		93.6	

* 1 atm. = 1.033 kg. per sq. cm.

As regards the magnitude of the effect of uniform pressure in raising the melting-point of a pure silicate, there are no experimental data; but the initial slope of the melting-curve could be calculated if the latent heat and volume change on melting were known. The relevant evidence is very scanty and unsatisfactory; but, so far as it goes, it indicates that the latent heat is of the order of 100 cal.[1] per gram and that the volume change ranges up to 10

[1] With regard to this estimate see: J. H. L. Vogt, *Die Silikatschmelzlösungen*, II (1904), 65; W. P. White, *Am. Jour. Sci.*, XXVIII (1909), 486 (footnote); G. Mulert, *Z. anorg. Chem.*, LXXV (1912), 238.

per cent,[1] or about 0.04 cc. per gram. On this basis[2] the rise of melting-point of a *pure* silicate produced by a pressure of 1,000 atm. would range up to 15°, with a possibility of a somewhat greater rise in exceptional cases (specifically, whenever the latent heat is small, unless the change of volume is at the same time very small). Accordingly, the change of melting-point would be of the order of 6° for the first mile in depth, an amount which, in all probability, would with each succeeding mile decrease steadily at a steadily decreasing rate, but would not become zero.

Now the question arises—could the temperature gradient downward overtake the pressure gradient? It would seem that this possibility is not to be excluded, for, according to the best evidence (likewise very scanty), the increase in temperature for one mile in depth is about 40° C.; consequently, if we assume that this gradient and the melting-curve gradient remain constant, the temperature would at a depth of 35 miles be 1,400° C., the approximate temperature at which many pure silicates exposed to the pressure existing at that depth would melt.

The foregoing reasoning applies only to a pure silicate melting to a liquid of its own composition; but to reason from the behavior of a single pure substance to its behavior in contact with a complex solution is of doubtful utility. For in the latter case the relative *solubility* of the substance in the solution under the particular conditions obtaining is the decisive factor which determines whether it shall separate, though of course it will not separate unless it would normally be solid (crystalline) at the prevailing temperature and pressure; and, so far as experience goes, pressure has very little influence on solubility in condensed systems (that is, systems without a vapor phase). The foregoing serves to emphasize the fact that any conclusions as to what will happen to rocks at high temperatures and pressures must still be considered to be subject to very serious limitations.

Reversible transformation points solid $\rightleftarrows$ solid (that is, enantiotropic inversions) are altogether analogous to melting-points, and

[1] See Day, Sosman, and Hostetter, *Am. Jour. Sci.*, XXXVII (1914), 1; cf. the results cited by R. A. Daly, *Am. Jour. Sci.*, XV (1903), 276.

[2] $\Delta T = \frac{T\Delta V}{41.3\Delta H} \times \Delta P = \frac{1,500 \times 0.04}{41.3 \times 100} \times 1,000 = 15°$ for 1,000 atm.

consequently the reasoning with regard to the shape of the melting-curve is, *mutatis mutandis*, applicable here; with this difference, however, that a maximum on the transformation curve is possible, since there appears to be no necessity that the solid form stable at the higher temperature should always have the greater specific volume. On the other hand, nothing whatever can be predicted as to the influence of pressure on monotropic (apparently irreversible) transformations, such for example as marcasite→pyrite, or aragonite→calcite; for such inversions take place whenever and wherever their rate becomes appreciable. Consequently the temperature region within which a monotropic inversion takes place varies with the conditions, especially such as the presence of a solvent; but there is no evidence that uniform pressure accelerates such transformations at all.[1] This conclusion is borne out by the fact that high pressure acting on either marcasite or aragonite was absolutely without effect in inducing the transformation to the more stable form. In this connection, however, it is to be remarked that it is possible that an inversion which is monotropic at one pressure may at another pressure be enantiotropic; no actual case of this is known, but this is not surprising in view of the small amount of work hitherto carried out under a wide range of pressures.

Very frequently rise of temperature causes one crystal form to change over into another (e.g., quartz→tridymite→cristobalite); rise of pressure (at constant temperature) in many cases produces a precisely analogous result—in other words, certain modifications are really stable only at high pressure. It follows that investigation of pure substances over a wide pressure range will frequently result in the discovery of hitherto unknown modifications of those substances. A beautiful example of this is the substance water, of which no fewer than five solid modifications are now known;[2] the relations between these are given in Table II and also in Fig. 1,

[1] The influence of pressure on rate of reaction in condensed systems has been investigated in very few cases: apparently it is very small, and may be either an acceleration or retardation. See E. Cohen and R. B. de Boer, *Z. physik. Chem.*, LXXXIV (1913), 41; E. Cohen and H. F. G. Kaiser, *Ibid.*, LXXXIX (1915), 338.

[2] P. W. Bridgman, *Proc. Am. Acad.*, XLVII (1912), 439–558; for other examples see Bridgman, *Physic. Rev.*, III (1914), 153–203.

which shows the fields of stability of the several forms and the several melting and transformation curves. From the diagram it is evident that if we keep the temperature constant at $-20°$, and increase the pressure gradually, the following sequence of events will occur: at 2,000 atm. ice I will melt, but the liquid will freeze again to ice III at 2,500 atm.; this in turn will pass over into ice V at 3,500 atm. which at 6,300 atm. will pass over into ice VI. At any temperature above 0°, no solid would appear until the pressure exceeded 6,400 atm. when ice VI would appear at a pressure depending on the temperature, e.g., 20,000 atm. at $+73°$.

TABLE II

NUMERICAL DATA PERTAINING TO THE EQUILIBRIUM DIAGRAM FOR WATER—LIQUID AND FIVE SOLID FORMS* (AFTER BRIDGMAN)

Pressure kg. per sq. cm.	Corresponding Temperature	Phases in Equilibrium
1	0.0	Freezing-point: ice I–liquid
1,000	− 8.8	" " " "
2,000	−20.15	" " " "
2,115	−22.0	Triple point (*A*): ice I–ice III—liquid
2,170	−34.7	" " (*B*): " " —ice II
3,510	−24.3	" " (*C*): ice III–ice V—ice II
3,530	−17.0	" " (*D*): " " —liquid
4,500	−10.2	Freezing-point: ice V–liquid
5,500	− 4.2	" " " "
6,380	+ 0.16	Triple point (*E*): ice V–ice VI—liquid
8,000	+12.8	Freezing-point: ice VI–liquid
12,000	+37.9	" " " "
16,000	+57.2	" " " "
20,000	+73.6	" " " "

* The notation ice IV was not used, as it had already been assigned by Tammann to another reputed form, which differs little from ordinary ice (I): the existence of this form, which was not encountered by Bridgman, is very doubtful.

Nor must it be supposed that the foregoing example is exceptional; indeed, it is now certain that polymorphism—i.e., the ability of a single chemical substance to appear in more than one crystalline form—is of frequent occurrence, even without the intervention of change of pressure. For example, sulphur exists in at least four forms, silica in at least six forms, etc. Now the form stable under high pressure may persist at ordinary pressure, just as high-temperature forms may persist at ordinary temperature; we may expect, therefore, that extended pressure investigations

will yield substances hitherto unobtained or even unknown, some of which might prove to be of technical importance. An illustration of this is the new form of phosphorus recently discovered by Bridgman;[1] this form is grayish black like graphite, has a high density (2.69, as against 2.34 for the red variety and 1.9 for the yellow), is ignited with difficulty by a match, and cannot be exploded by a blow from a hammer, as red phosphorus can. Never-

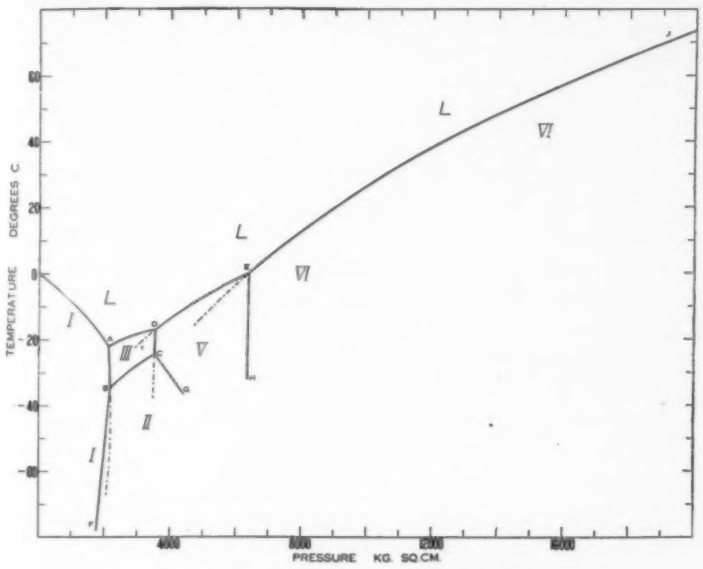

FIG. 1.—Equilibrium diagram for water—liquid and five solid forms

theless it is probable that uniform pressure has been essential to the formation of but few ordinary minerals, except in so far as it was effective in securing an adequate concentration of some volatile component (or components) in the magma from which the minerals separated.

So far we have taken up the effects of pressure upon a single pure substance; when we deal with systems of more than one

[1] P. W. Bridgman, *Physic. Rev.* III (1914), 187.

component, the mutual solubilities[1] enter as factors in the result. These are affected by pressure because it changes the relative concentrations or activities of the several components. This influence is slight with solids and liquids, because their compressibilities are very small; but in systems with a gaseous phase it is very great, because the concentration of a gas is directly proportional to the pressure, so that in such systems change of pressure will have a marked influence on the relative concentrations of the several reacting components.

In accordance with this, the influence of uniform pressure upon solubility and upon chemical equilibrium in condensed systems—that is, systems in which there is no vapor phase—is slight, and for practical purposes negligible in comparison with the influence of temperature or change of composition of the solution. Thus the few trustworthy experiments made hitherto show that a pressure of 1,000 atm. changes the solubility of a salt in water by only about 1 per cent of its value—a change which may readily follow a temperature change of a few degrees or a slight change of composition of the solution.[2] Again, at ordinary temperatures the liquids water and methylethylketone are only partially miscible at 1 atm., but they become completely miscible at about 1,100 atm.,[3] whereas at 1 atm. this does not take place until a temperature of 152° is reached. The opposite effect—i.e., unmixing by increase of pressure—could equally well be produced, just as it may be by increase of temperature. But it seems probable that neither of these effects is of importance in liquid mixtures of silicates, because liquids which

[1] It is to be remembered that mutual solubilities can be altered by the addition of a third component, even though it forms no part of the solid phase which separates. Thus, as is evident from fig. 6 of Rankin's paper (*Am. Jour. Sci.*, XXXIX [1915], 1–78), a mixture composed of 60 per cent SiO_2, 40 per cent Al_2O_3, on cooling deposits Al_2SiO_5 (sillimanite), whereas in presence of CaO, in amount ranging from 3 to 30 per cent of the whole, the solid phase which separates is *pure* Al_2O_3. This illustrates how even a small change in composition of a solution may alter the course of crystallization.

[2] E. Cohen and L. R. Sinnige, *Z. physik. Chem.*, LXVII (1909), 432; LXIX (1909), 102; E. Cohen, K. Inouye, and C. Euwen, *ibid.*, LXXV (1911), 257. These authors give a critical résumé of earlier work along this line.

[3] P. Kohnstamm and J. Timmermanns, *Proc. K. Akad. Wetenschappen*, XV (1913), 1021–37.

are so much alike chemically as are the silicates are usually completely miscible under all conditions.

But the effect is of another order of magnitude in presence of a gas phase which may enter into reaction or solution with other components; and consequently this circumstance must be taken into consideration in any discussion of the behavior of the magma, which undoubtedly contains volatile components of this character.

TABLE III

THE SOLUBILITY* OF $CaCO_3$ AT 16° AND ITS DEPENDENCE UPON THE PARTIAL PRESSURE OF CO_2 OVER THE SOLUTION

Partial Pressure of CO_2 in Atmospheres	Solubility Parts $CaCO_3$ per Million Parts Water
0.0	14.3
0.00037	46.1
0.00050	74.6
0.0033	137.2
0.0139	223.1
0.0282	296.5
0.0501	360.0
0.142	533.0
0.254	663.0
0.417	787.0
0.553	885.0
0.730	972.0
0.984	1,086.0

* Data according to Schloesing (*Compt. rend.*, LXXIV [1872], 1552; LXXV [1872], 70, except the first two, which are due to Kendall [*Phil. Mag.*, XXIII (1912), 958–76]).

As a simple example, consider the amount of $CaCO_3$ which will dissolve in water inclosed in a vessel with various partial pressures of CO_2. In pure water it is 14 parts per million, an amount which is trebled by the presence of as little as 0.00037 atm. CO_2 (3.7 parts in 10,000, about the proportion of CO_2 in ordinary air) and has increased by more than 70 times when the CO_2 pressure reaches 1 atm. (see Table III). This great increase is an example of the very great effect of increase of concentration (partial pressure) of a gaseous component; it is, of course, due to the formation of calcium bicarbonate in the solution, but this circumstance in no wise affects the force of the argument. Indeed, this is an excellent illustration

of the law of mass action, as the calculations made by Stieglitz show.[1]

A closely related point is that a compound resulting from a reaction involving a volatile component will not be formed unless the concentration—in other words, the partial pressure—of that component is above a certain limiting value, this value being dependent on the conditions, on the temperature especially. An illustration may serve to make this clearer. If we wish to keep liquid water at 200° we must have it in a closed vessel capable of withstanding the vapor pressure of water at that temperature, which amounts to about 15 atm. (225 lbs. per sq. inch); likewise at 300° the vessel would require to be strong enough to support an internal pressure of 100 atm.; but if the vessel should leak, either because it was not strong enough or because it was not tightly closed, the vapor would escape and the liquid water would disappear. Similarly we can keep $Ca(OH)_2$ as hydroxide at 550° in steam at 1 atm., but at 750° it would be necessary to have a pressure of water vapor of about 15 atm. (and at 950°, about 100 atm.) if we wish to retain it all as hydroxide and to have no oxide present; in other words, if we should wish to prepare $Ca(OH)_2$ from CaO at a temperature of 750°, we could do so only by having continuously a pressure of at least 15 atm. of water vapor above it.

It may happen, therefore, that the product which actually separates in certain cases will be determined by the magnitude of the pressure of water vapor at the time of separation. This serves to account for the fact that the biotite of many deep-seated igneous rocks is replaced in their effusive forms by olivine and leucite (which are in the aggregate chemically equivalent to biotite from which water has escaped)—a relation which has been brought out by Iddings, Bäckstrom, and others. Similarly, muscovite is found only in granitic rocks consolidated at depth, while in their surface equivalents the water has in part escaped and the potash has entered feldspar and biotite.

[1] J. Stieglitz, "The Relations of Equilibrium between the Carbon Dioxide of the Atmosphere and the Calcium Sulphate, Calcium Carbonate, and Calcium Bicarbonate of Water Solutions in Contact with It," *Carnegie Institution of Washington, Publication No. 107* (1909) (*The Tidal and Other Problems*, by T. C. Chamberlin *et al.*), pp. 235–64.

A noteworthy point in this connection is that water vapor—or, for that matter, any volatile component—may, and does, act in a way precisely analogous to any non-volatile component, the only difference being that it in general requires pressure in order to hold it on the job, so to speak. As an illustration, let us consider the equilibrium diagrams in Fig. 2, I for the system $LiNO_3$–KNO_3, II for the system H_2O–KNO_3, III for the system H_2O–CrO_3. In I, *L* is the melting-point of pure $LiNO_3$, which by admixture of KNO_3 is lowered along the line *LE:* this line therefore represents the equilibrium between solid $LiNO_3$ and liquid mixtures of $LiNO_3$ and KNO_3 of various compositions; in other words, it is the solubility curve of $LiNO_3$ in these mixtures. Similarly *KE* represents the equilibrium between solid KNO_3 and liquid. These two curves meet in *E*, the so-called eutectic point, at which point (132°) a liquid of the composition 45 per cent $LiNO_3$, 55 per cent KNO_3 freezes to an agglomerate of the same composition. In II, point *I* is the freezing-point of water, and *IC* the freezing-point of solutions of KNO_3; in other words, *IC* is the equilibrium line along which ice is in equilibrium with mixtures of H_2O and KNO_3 of various compositions. The line *KC* represents the equilibrium between solid KNO_3 and mixtures of KNO_3 and H_2O; the end nearer *C* is the ordinary solubility curve of KNO_3 in water, while toward *K* it would be more logically called the solubility curve of H_2O in KNO_3. The curves meet in *C*, which in the case of aqueous solutions is usually called the cryohydric point. These two systems are thus obviously altogether similar, the sole difference resulting from the difference in the vapor pressures of H_2O and $LiNO_3$ in relation to the prevailing atmospheric pressure; namely, that whereas at the temperatures concerned the vapor pressure of $LiNO_3$ is inappreciable, that of water ranges from some millimeters up to many atmospheres. The equilibrium curve (III, Fig. 2) for the system H_2O–CrO_3 is included because in form it resembles very closely that for $LiNO_3$–KNO_3; the branch of the curve on the water side is much longer than in the case of H_2O–KNO_3, corresponding to the much greater solubility of CrO_3 in water at and below 0°.

At each point on the curve *CK* the liquid in equilibrium with solid KNO_3 has a definite composition and therefore a definite vapor

pressure of water which must be maintained in order to secure the appropriate concentration. This vapor pressure becomes equal to 1 atm. at about 120° (the ordinary boiling-point of a saturated aqueous solution of KNO_3); increases, as we ascend the curve, to a maximum, which in this case is only 2 or 3 atm., and finally decreases to zero at the point K. In systems such as this—namely, in which the liquid may have (under the appropriate conditions)

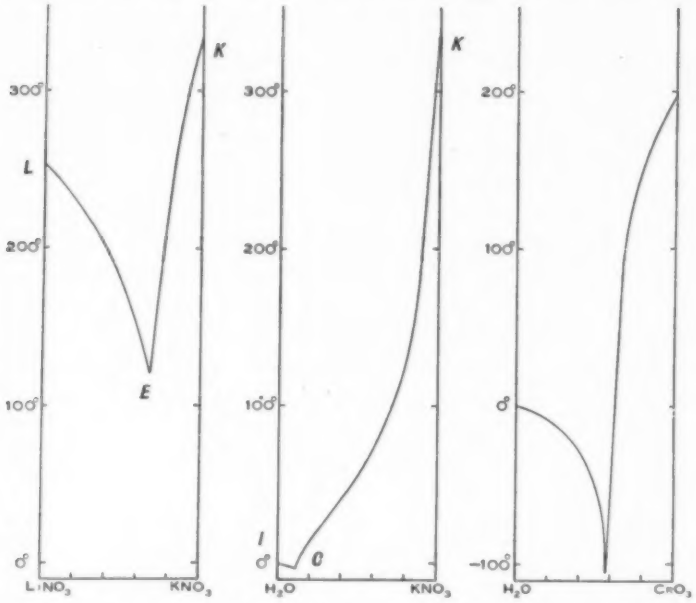

FIG. 2.—To show the similarity between the equilibrium diagrams of the system $LiNO_3$–KNO_3, H_2O–KNO_3, H_2O–CrO_3.

any composition ranging from one pure component to the other—the magnitude of the maximum equilibrium pressure depends mainly on the melting-point of the salt; where the melting-point is low, as for KOH, the maximum pressure is less than 1 atm.; where it is high, as for potassium silicate, the maximum is some hundreds of atmospheres. Nevertheless, as is evident from the diagram, the lowering of melting-point produced by a comparatively

small amount of water may be quite large; for it would seem that a lowering of 100° could easily result from the presence of water vapor at a pressure less than 20 atm. Incidentally it may be pointed out that the circumstance that pure water has a critical point at 370° and 200 atm. is of secondary importance in the discussion of systems belonging to this type.[1]

The great similarity exhibited by these two systems shows that there is no real difference between melting-curves and solubility curves; a simple and well-known illustration of this is the fact that the melting-point of $CaCl_2 6H_2O$ to a liquid of its own composition is merely a particular point on the graph representing the solubility of $CaCl_2$ in water. In general it is much simpler to consider all such phase diagrams as solubility diagrams, as by so doing it is easier to grasp their full significance and to predicate what will happen under specified circumstances. This point was clearly stated thirty years ago by Guthrie, the first investigator of eutectics, who wrote as follows:[2]

> [My experiments show] that water at a high temperature may not only play the part of a solvent in the ordinary restricted sense, but that there is in many cases no limit to its solvent faculty; in other words, that it may be miscible with certain rocks in all proportions: that solution and mixture are continuous with one another. And this continuity, as my experiments prove, is established in some cases—and these indeed with bodies having no chemical affinity with water—at temperatures not above the temperatures of fusion of those bodies *per se*.

Moreover, Guthrie saw the geological significance of these results, for he wrote:

> Just as in the selective formation of salt-alloys we may have the artificial type of the genesis of many primary rocks and metamorphic modifications, so in the wonderful solubility in or miscibility with water of such alloys and of some salts at high temperatures we may have a no less clear type of the formation of certain volcanic rocks and an explanation of some of their peculiarities. . . . . Obsidian melted and under pressure will, I presume, mix freely with water. When this pressure is gradually removed, water vapor escapes, and although it takes with it a large amount of heat, the temperature of the obsidian

[1] With regard to this point see Morey and Niggli, *Jour. Am. Chem. Soc.*, XXXV (1913), 1089 ff.

[2] *Phil. Mag.*, XVIII (1884), 117.

may still remain above its point of anhydrous fusion, or it may be maintained fused by heat from other sources. Finally cooled, it is the familiar glassy amorphous mineral. A quick release of pressure entails a quick vaporization of water and a quick loss of heat. The obsidian mass, during and because of the loss of water and the loss of heat, becomes pasty and "rises" like dough during fermentation, and becomes pumice, which is often found overlying obsidian. A quicker release of pressure from above causes the vesicular and vesiculating masses to be projected, and if the vesiculation is carried far and fast, volcanic dust is produced.

The phenomena discussed in the paragraph just quoted have now been realized experimentally with potassium silicates by Morey, who was able to produce at will either a hard or a pumiceous glass merely by altering the mode of cooling.[1]

What has been said about systems containing volatile components may be applied to elucidate some aspects of the behavior of of a cooling magma. If the crystals separating out initially from a magma situated within a confined space contain none of the volatile component, then the concentration of the volatile component in the residue would become continuously greater, and consequently the vapor pressure would *increase;* this increase might under certain circumstances be large, so that there would be a considerable tendency to enlarge the space within which the magma is confined. Accordingly eruption of a magma may be correlated with a comparatively early stage of its crystallization. On the other hand, the initiation of crystallization may be due to the circumstance that the pressure was relieved—by faulting in the adjacent rock, or otherwise—whereupon the magma began to lose its volatile components, and consequently to crystallize; this process is precisely analogous to the crystallization of a salt from a solution by boiling off the solvent.

If no escape is possible, the residue from the crystallization of the main portion of the non-volatile constituents will be a *fluid* (as distinct from a liquid) solution, containing silicates and probably sulphides, etc., which is so mobile that it can easily penetrate the adjacent rock, producing the phenomena of contact metamorphism and injection. Thus we can account for the very thin veins and dikelets often observed at igneous contacts, which indicate that at

[1] G. W. Morey, *Jour. Am. Chem. Soc.*, XXXVI (1914), 226–27.

some period the rock was permeated by very mobile solutions from which crystals subsequently separated while the still volatile components passed on. It was presumably in some such way that the pegmatites formed, for there are other reasons for believing that they formed at about 600°, a temperature at which all their constituent minerals would long have been solid had there been no volatile components present.

SUMMARY

In the foregoing pages is presented a brief discussion of some aspects of the influence of pressure on the formation of rocks and minerals. In general it would seem that the importance to geology of the effects of pressure upon so-called physical changes (e.g., the melting-point of a single pure substance) has been overestimated relatively to that of the influence of pressure upon chemical changes —in other words, upon equilibrium in polycomponent systems. Change of effective pressure will in general change the configuration of the various fields of stability in a system, acting thus in a way precisely analogous to change of temperature, or of gross composition; but in the case of pressure the effect will usually not be especially marked unless one or more of the components is volatile—that is, unless the concentration of one or more of the components really changes appreciably with change of pressure. This is merely an example of the general rule that the magnitude of the effect of pressure on a system depends upon the difference in compressibility of the several phases present, being greatest when this difference is greatest, and conversely.

Accordingly we must, in any discussion of the course of crystallization from a complex magmatic system, take into account the mode in which the effective pressure varies as well as the mode of cooling. For change of pressure, like change of temperature, may affect the order of crystallization—and even the character—of the minerals which separate; this result of course depending merely upon the circumstance that the saturation limits (solubilities) of the several solid phases which could possibly separate out are not all affected equally by change of conditions.

January 29, 1915

TWO GLACIAL STAGES IN ALASKA[1]

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The existing glaciers of Alaska are of such wide distribution and are such striking scenic features that they have attracted the attention of many glacialists. The coastal glaciers, many of which are of large size and relatively accessible, have been most frequently visited and described, and the literature on Alaskan glaciers now includes a large number of titles. The fact has been generally recognized by those who have studied the glaciation of this territory that the area at present covered by glaciers is much smaller than the area which was formerly covered by glacial ice, and glaciers no longer exist at many localities where the surface still shows conspicuous evidence of their former presence. This evidence consists of such physiographic features as typical glacial mountain valleys, U-shaped in cross-section; glacial lakes; moraines and hanging tributary valleys, and of such other evidence as is afforded by smoothed, polished, and striated rock surfaces; glaciated pebbles and bowlders; erratic bowlders, and deposits of glacial till.

It is beyond the scope of this paper to outline the areas in Alaska which are known to have been formerly covered by glacial ice. Brooks[2] published in 1906 a map showing the limits of glaciation, as known at that time. Tarr and Martin[3] have recently published a revision of Brooks's map, based on somewhat more recent information. On both of these maps a number of areas have been shown as glaciated about which no detailed information is available, and the outlines as given can be corrected only after much more field work has been done.

[1] Published by permission of the Director of the U.S. Geological Survey.

[2] A. H. Brooks, "Geography and Geology of Alaska," *U.S. Geol. Survey Paper 45*, 1906, Pl. XII.

[3] R. S. Tarr, and L. Martin, *Alaskan Glacier Studies*, National Geographic Society, 914, Map 1.

All attempts to map the limits of glaciation in Alaska have been made upon the assumption that the ice reached its greatest extension during the last great glacial advance, the evidence of which is so conspicuous, and that the limits of glaciation as shown are the limits reached by the ice during this period of expansion. Up to the present time no facts had been obtained which would show the age of this last great ice advance, as compared with any of the various stages of continental glaciation. Furthermore, although by analogy one might expect that the glaciers of Alaska would have been influenced by the same general climatic conditions which affected the main body of the continent, and would have advanced and retreated contemporaneously with the continental glaciers, yet for a period of fifteen years, during each summer of which geologists have been in the field observing glacial phenomena, the problem of whether or not there have been recurrent glacial stages in Alaska has continued to present many uncertainties. In 1890, and again in 1891, I. C. Russell[1] observed on the southern slopes of Mount St. Elias certain elevated marine deposits of fine clastic sediments containing bowlders which he believed to be of glacial origin. The same terrane was observed, in 1913, by A. G. Maddren[2] in the Yakataga district, and his interpretation of the origin of the bowlders is in agreement with that of Russell. The published literature for the most part, however, fails to discuss the probability of earlier stages of glaciation in Alaska, although the writer[3] has suggested that there may have been earlier glacial advances, but if so, they were less extensive than the last, and the traces of such glacial advances were destroyed or obscured by the more extensive and more recent ice invasion.

During a geologic reconnaissance trip into the White River basin, in the summer of 1914, observations were made which seem to throw light both upon the age of the last great ice advance and

[1] I. C. Russell, "An Expedition to Mount St. Elias," *Nat. Geog. Magazine*, III (1891), 170–73; also "Second Expedition to Mount St. Elias in 1891," *13th Ann. Rept. U.S. Geol. Survey*, Part II (1893), pp. 24–26.

[2] A. G. Maddren, "Mineral Deposits of the Yakataga District," *U.S. Survey Geol. Bull. 592*, 1914, pp. 131–32.

[3] S. R. Capps, "The Bonnifield Region, Alaska," *U.S. Geol. Survey Bull. 501*, 1912, pp. 35–36.

upon the problem of whether or not there have been recurrent glacial stages in Alaska. The first of these problems has been discussed elsewhere,[1] and the mere statement will suffice here that the last great ice advance was probably contemporaneous with the Wisconsin continental glaciation.

Near the source of White River in Russell Glacier and lying between Lime and Solo creeks, two of its tributaries, there are certain foothills of the mountains which in 1908 were seen by the writer to consist for the most part of gravels, but no careful study of this section was then made. In the summer of 1914 a

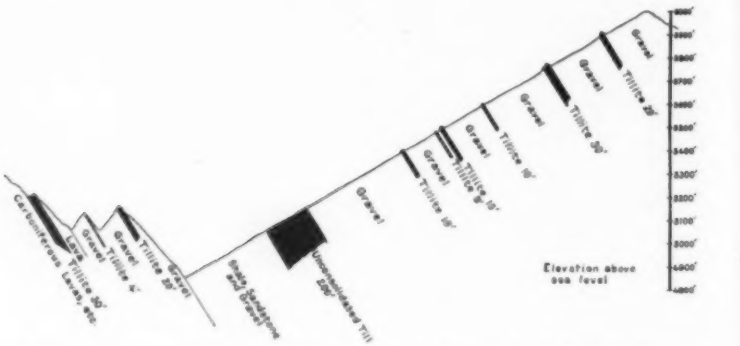

FIG. 1—Diagrammatic section of older glacial deposits near head of White River

single day was available in which to revisit this locality, and heavy rains and fog during that day prevented as thorough an examination as was desirable. The section shown in the accompanying figure (Fig. 1) is therefore not complete and the thicknesses given are only approximate, but nevertheless certain important facts are made clear. In the section to be described the exposure is unusually good, the surface of the hills being almost entirely free from vegetation, and cut by a number of clean, steep-sided gullies so that practically every foot of the deposit is exposed (Fig. 2).

The section, covering a vertical range of 1,150 feet, shows a great thickness of unconsolidated gravel beds, with some soft shales

[1] S. R. Capps, "An Estimate of the Age of the Last Great Glaciation in Alaska," *Jour. Wash. Acad. Sci.*, V, No. 4 (1915), 108–15.

FIG. 2.—The older glacial deposits form the hill near the center of the picture. The lenticular beds, which project above the general slope, are lenses of tillite, separated by unconsolidated gravels and unindurated till.

and a little sandstone, interrupted by sheets and lenses of glacial till in varying stages of induration, and by lava flows. Measured perpendicular to the dip, more than 3,000 feet of beds were examined, and the thickness of the upward continuation of the series is not known, but is considerable. The gravels, which comprise much the greater part of the entire thickness, are well rounded but only fairly well assorted, and are apparently stream-laid. The pebbles are composed of the Carboniferous lavas and limestones which form the mountains immediately adjoining to the southwest. In one place a considerable thickness of arenaceous shales and sandstones occurs. Only one lava bed is shown in Fig. 1, but in other near-by localities similar lenticular lava flows were seen much higher in the section, and farther east, on North Fork of White River, the glacial series here described is overlain by lavas of considerable thickness.

The tillite beds, while forming only a small proportion of the whole series, are nevertheless the most conspicuous members of it, for their outcrops are left in high relief by the removal of the softer surrounding materials. The uppermost bed shown in the figure in places forms the crest of the ridge and stands up in high ragged pinnacles (Fig. 3). The tillite exactly duplicates, except for its induration, the ordinary glacial till which is of such widespread distribution throughout this general region. It has a clayey matrix full of small, angular particles of rock and incloses abundant pebbles, bowlders, and angular fragments of rock, many of which are several feet in diameter. The included bowlders and blocks are of the materials which compose the mountains to the southeast and are mostly of basic extrusive rocks of brown, purple, and reddish color, and the matrix has a slight purple tinge.

Striae were found abundantly on many bowlders, especially on those of fine texture. Large bowlders in particular showed plentiful striations, but typically striated hand specimens were not easily found. The characteristic subangular bowlders, so typical of glacial deposits, are plentiful throughout the tillite, and the whole aspect of these beds leaves no doubt of their glacial origin. A number of striated and subangular pebbles were broken from the hard matrix, and numberless other larger, but equally characteristic,

striated and subangular bowlders were found imbedded in it, so that no suspicion can be entertained that the glaciated bowlders were deposited upon the surface at this place by a later glacier.

FIG. 3.—Close view of a tillite bed

In the particular part of the section measured, and shown in Fig. 1, there are nine beds of tillite, ranging from 4 to 30 feet in thickness, and one bed of uncemented glacial till, much covered by waste from above, but apparently at least 200 feet in thickness. Probably no other portion of the section would be like that figured,

for the tillite beds are lenticular in the cross-section exposed and probably also down the dip. The uppermost tillite bed shown is, however, known to persist along the strike for at least a mile, though its thickness is variable.

On North Fork of White River, about 6 miles east of the locality here described, similar tillite beds are exposed in the canyon of that stream and are there overlain by lava flows. The lava bed shown near the base of the section and other lava flows interbedded with the gravels and tillite higher in the series, but not at this particular place, are brightly colored, reddish, scoriaceous lavas, like the flows which are so generally distributed throughout the Wrangell Mountains. They range in age from Tertiary to Recent, and Mount Wrangell even now shows signs of mild activity.

As already stated, the evidence seems fairly definite that the last great ice advance in the White River valley was contemporaneous with the Wisconsin stage of continental glaciation. Till left by the ice during this advance is of widespread distribution in the White River basin, and wherever observed is unconsolidated and little oxidized. At one point at the edge of the Lime Creek gravel flat, about $2\frac{1}{2}$ miles from the locality of the section shown, the unconsolidated till of the last ice advance was found lying unconformably upon the upturned and glaciated edges of the older tillite, proving definitely that the tillite series was laid down during a glacial advance which antedated the last ice invasion. Furthermore, a long time-interval between the two glacial advances is indicated by the induration of the tillite and by its deformation since it was deposited. The physiographic evidence at hand also goes to show that the older tillite was indurated and uptilted and a mature topography eroded upon it before the last great glacier remodeled the surface and left its morainal deposits.

The tillite series here discussed is thought to have been laid down near the oscillating edge of a glacier. The record shows repeated advances, with deposits of morainal material, followed by recessions during which the till was covered by outwash gravels from the ice front, and one period during which finer sediments, represented by the shales and sandstones, were laid down. These materials may represent lake deposits. There were also occasional

extrusions of lava over the surface of till and outwash. The lenticular shape of the tillite beds may be due either to the shape of the original morainal beds, or to local erosion following a time of ice recession. The lack of induration of one thick till bed may have been due to the impenetrability of the till itself, or of the underlying shale, and is not believed to affect the general interpretation of the section. The whole series of beds, with the exception of the lava flows, is probably similar to the deposits now being laid down near the terminus of many a glacier in this same mountain range.

Little can now be said of the areal extent of the glacier which left these old morainal deposits. The elevation of the present exposures is of little importance, for the beds show by their structure that they have been tilted, with minor folding, and their present elevation may be much different from that at which they were laid down. At present the 3,000 feet of the beds described are seen within a vertical range of only 1,150 feet. The beds at this locality dip from 55° to 60° to the east, but the dips gradually become less as the distance from the mountains increases, and as seen in the canyon of North Fork of White River the tillite is nearly flat-lying. All the known outcrops of tillite lie well within the limits reached by the ice during its last great advance, and no comparison can yet be made of the extent of the ice fields during the two stages.

Summary.—There have now, for the first time, been found in Alaska deposits of glacial till which can be proved to antedate by a considerable period of time the last great ice expansion, thus proving that there have been at least two distinct glacial stages in that territory. The deposits comprise a series having a thickness over 3,000 feet and consist of indurated as well as unconsolidated glacial till sheets, separated by outwash gravels and some assorted sediments, and interrupted by lava flows. The section examined was evidently deposited near the border of an oscillating ice edge and shows ten definite advances of unknown magnitude, represented by the deposition of till beds, followed by periods of retreat during which water-laid beds were deposited upon the successive till beds. After its deposition this series of glacial and glacio-fluvial beds was covered by lava flows, at least locally, was uplifted, in part indurated, and was later deeply cut by erosion. A much later ice

advance, probably contemporaneous with the Wisconsin continental glaciation, then took place, overriding the earlier glacial deposits and locally capping them with later till beds. The extent of this earlier glacial advance, as compared with the last great stage of glaciation, is not known, all of the observed deposits of older glacial material lying far within the outer limit of the last great glaciation. Enough data have not yet been obtained upon which to base a correlation of the older glacial deposits with the earlier stages of continental glaciation.

STRATIGRAPHY OF THE WAVERLY FORMATIONS OF CENTRAL AND SOUTHERN OHIO (*Continued*)

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PART II

CUYAHOGA FORMATION (*continued*)

THE SCIOTO VALLEY SHALE FACIES

Extent and Thickness.—The Scioto River from Chillicothe to Portsmouth flows roughly along the axis of this area. Here the Cuyahoga is constituted almost entirely of bluish-gray clay shale with only an occasional sandstone bed. To the eastward, as the margin of the Hocking Valley conglomerate facies is approached, sandstones become more numerous and increase in thickness. A similar increase in sandstone content is experienced to the westward, as the Vanceburg sandstone facies is approached. These transitional sandstones are, however, of a different type on opposite sides of the shale area. On the eastern side are found hard, coarse sandstones (but finer grained than the Hocking Valley sandstones) that are peculiarly harsh to the touch; they are reddish-brown on the outcrop, light greenish-blue under cover, and *Spirophyton* is not present to any extent. Beds of this type persist as far west as the Scioto River, where they may be four or five feet thick, and some of the beds can be traced for several miles. On the western side of this shale facies, the sandstones are of the type which characterizes the Vanceburg facies, to be described presently, but distinguished particularly by their soft, clayey nature, light yellowish color on the outcrop but blue-gray under cover, and abundance of *Spirophyton*. One member only of the latter type persists any considerable distance into the shale area, the Buena Vista member, and it may be found in some sections east of the Scioto River in the presence of sandstones that have obviously been derived from the eastward, but even in the same section

each exhibits the characteristics of its respective type little changed.

The Cuyahoga over the shale area is not as thick as in the Hocking Valley facies. Between Chillicothe and Waverly it is about 300 feet thick and at Portsmouth about 300 or 320 feet. West of the Scioto River near Portsmouth it falls to about 260 feet.

Members.—Three members are distinguished. At the base is the *Henley shale member* which apparently attains a thickness of over 200 feet. This is succeeded by the *Buena Vista sandstone member*. Since both are recognized in the Vanceburg sandstone facies, their description is better reserved for that place.

The name *Portsmouth* is applied to the upper shale member from Portsmouth, where it is excellently exhibited on both sides of the Scioto River, and on the Ohio River above the town. At the "Two-Mile Hill" at Portsmouth it is 253 feet thick, but this decreases to the northward and westward. The Portsmouth shale is the equivalent of the three upper members of the Vanceburg facies. It is impossible, at present, to present correlations between the members of the Scioto Valley shale facies and those of the Hocking Valley conglomerate facies to the eastward. All that can be suggested is that the Buena Vista sandstone is not the equivalent of any one of the four members distinguished there; its horizon is probably near the middle of the deposits in the Hocking Valley. Further, it appears that the upper part of the Portsmouth shales at Portsmouth—how much is not known, but perhaps 50 feet or more—is the stratigraphic equivalent of the lower part of the Byer member of the Logan formation only six miles up the Ohio River at Sciotoville.

THE VANCEBURG SANDSTONE FACIES

Extent and general nature.—This is confined to the western parts of Scioto and Pike and the southwest corner of Ross counties, with some extension into Adams County. The facies proper lies well west of the Scioto River. The thickness of the Cuyahoga appears to be about 250 feet, of which the lower 150 feet or more are made up largely of sandstones, the upper 100 feet largely of shale.

The deposits which distinguish this facies differ greatly from those in the two sandstone and conglomerate facies just described. They consist of alternating beds of exceedingly regular sandstone and shale. The sandstones are usually from 6 or 8 inches to 18 inches in thickness, although they exceptionally attain 4 or 5 feet; they are very uniformly fine grained, blue-gray in color when unweathered, and persistently uniform in thickness for considerable distances. The shales not uncommonly are mere partings between these beds, but they may equal or exceed the sandstone beds in thickness. At McDermott the thin sandstone and shale beds are known to hold their characteristics individually over almost a square mile. The shales are thicker at the bottom and at the top and the persistent occurrence of a considerable amount of red shale in the lower part is one of the characteristic features of this facies and an unusual one in the Waverly.

The upper surface of each stratum of sandstone is covered by *Spirophyton* markings, the tubes of which penetrate downward through the upper 4–8 inches in infinite numbers. The under surface of each sandstone is usually traversed by many raised lines and elongate rootlike ridges in various degrees of prominence which are merely the casts made by the sand settling in the scratched and gouged upper surface of the underlying shale partings. These structures indicate a peculiar cycle of events that was repeated many times during the accumulation of the deposit: (1) accumulation of sands to a thickness of a foot or two; (2) period of quiet and invasion of the sandy floor by myriads of fixed worms (if *Spirophyton* is correctly interpreted as a worm tube); (3) deposition of a thin bed of clay mud and extermination of the worms; (4) intervention of some agent, probably bodies floating or trailing in shallow water, which scratched the muds but never, so far as observed, to a depth of over an inch; this completed the cycle and sands were again laid down. This was repeated many times but it is more striking in the lower part of the sandstones, where the shales are reduced to mere partings.

The deposit is marine, as is shown by the occasional finding of a sandstone bed which differs from the others only in the presence of a normal marine fauna of brachiopods, gastropods, cephalopods,

lamellibranchs, etc., in very great abundance often only for a few square feet; the composition and structure of such a deposit suggest that this accumulation where found was accomplished through current-action.

The deposits of this facies pass into the shales of the Scioto Valley shale facies to the eastward by disappearance of the sandstones. This transition takes place rather abruptly and practically all of the beds disappear simultaneously except those of the Buena Vista member, which persists far into the shale area. The original western margin of the Vanceburg facies in Ohio has been removed by erosion.

Five members can be recognized, of which all are persistent over the area of the facies, except the topmost, which has been removed by erosion at points in Pike and Ross counties. Although these members appear to be distinct stratigraphic units over much of the area, near the margins of the facies where the sandstones are disappearing certain of the boundaries obviously become of uncertain stratigraphic significance.

The Henley shale member is named from Henley, Scioto County. In the area of maximum development of the Vanceburg type of sandstones, it consists of alternating gray and red shales, but the red color disappears to the eastward, together with the sandstones of the facies. Along the western boundary line of Scioto and Pike counties this member gradually increases in thickness from $5\frac{1}{2}$ feet at Buena Vista and 9 feet at Vanceburg to $34\frac{1}{2}$ feet at Bainbridge in Ross County. Eastward and northeastward from this line of sections in the Scioto Valley shale facies the thickness increases rapidly, especially to the eastward. Along the Scioto River the thickness increases from $55\frac{1}{2}$ feet at Rushtown in Scioto County to 89 feet near Summit in Ross County. Several miles east of Piketon in Pike County, its thickness has increased to 226 feet, if the superjacent Buena Vista sandstone is correctly identified. The rapid westward thinning of this basal portion of the Cuyahoga is believed to indicate that the Cincinnati dome was an appreciable topographic feature on the shallow sea-floor of that time. There is, however, no physical evidence of erosion of the underlying thin Sunbury shale prior to its accumulation.

The name *Buena Vista* has been adopted for the second member in the Vanceburg facies.[1] For many years the village of Buena Vista was the center of extensive quarrying. The basis of the industry was a relatively thin sandstone member a few feet above the base of the Cuyahoga. Since the product was largely marketed in Cincinnati, the member came to be known as the "City ledge." It is to this member and its continuation over Scioto, Adams, Pike, and Ross counties that the name Buena Vista is here restricted.

The Buena Vista consists of sandstones of the type just described as characteristic of the facies. It is not, however, of the same quality, structure, and thickness in all parts of its area. Along the western margin of Scioto County it is usually from 3 to 6 feet thick and consists of from one to four distinct sandstone beds. Eastward from this and over the ever-thickening Henley shale,

[1] This name was first proposed by Edward Orton in his "Report on Pike County" (*Geol. Surv. Ohio*, II, Part I [1874], 626), where the lower 50 feet of the Cuyahoga formation was separated as the Buena Vista member. "As the most valuable of the building rock, however, that is furnished by this part of the series in southern Ohio occurs within 50 feet of the slate [Sunbury], these 50 feet next above the slate may be somewhat arbitrarily taken as a subdivision." Prosser has fully recounted the history of this usage and variation in usage of the term by Orton and has himself adopted it in the same sense as originally used (*Am. Geol.*, XXXIV [1904], 341, 342). It can readily be shown, however, that any member arbitrarily established on the lower 50 feet of the Cuyahoga over central and southern Ohio is wholly without foundation in fact. Stratigraphically there is no such member. The lowermost 50 feet will not include all of the valuable building stones, if this were an acceptable criterion for the establishment of such a member, since it does not include the stone at the only locality where such stone is now being worked, McDermott. The sediments forming the lower 50 feet from point to point are not even always similar; in some places it is sandstone, in others it is shale. It becomes necessary to redefine the term Buena Vista if it is to be used at all, and in the present statement it is applied to the "City ledge" of the quarrymen at Buena Vista, and its continuation throughout western Scioto and Pike counties. Orton has on one occasion (*Geol. Surv. Ohio*, V [1884], 602) used the term Buena Vista in this sense. Elsewhere he has used it apparently to denote the particular bed which he erroneously supposed to be the equivalent of the City ledge ("Report on Pike County," *Geol. Surv. Ohio*, II, Part I [1874], diagrams between pp. 618 and 619). Prosser, too, in an earlier publication used the term similarly (*Jour. Geol.*, X [1902], 289–91). The term thus redefined is not, then, used with a wholly new meaning.

The adoption of the term in Ohio with either of the meanings outlined antedates its application by H. D. Campbell to a formation in Virginia (*Am. Jour. Sci.*, 4th ser., XX [1905], 445–46), as pointed out by Prosser (*Am. Jour. Sci.*, 4th ser., XXI [1906], 181–82).

it increases in thickness to about 25 or 30 feet along the west side of the Scioto River well within the Scioto shale facies. Simultaneously the number of component beds increases. Farther east than this on the east side of the Scioto River, and northward over western Pike and southwestern Ross counties, its beds become more shaly and worthless. It remains, however, so far as traced, much the same type of deposit as characterizes the Vanceburg facies, even where, on the eastern margin of the Scioto shale facies, it becomes intertongued between those sandstones of a wholly different type that are clearly the western fringe bordering the Hocking Valley conglomerate facies. At the most easterly point where it was observed, however, several miles east of Piketon, the component beds are much thicker than a mile or two to the westward, and there is evidence that, as the Hocking Valley area is approached, the member increases in importance.

Westward from the western margin of Scioto County the Buena Vista member continues to thin, and within two or three miles of the zone where it is from 3 to 6 feet thick and economically important, it is less than a foot in thickness. It has not been traced westward beyond this but it probably thins out entirely. This is near the western limit of its outcrop belt.

The Rarden shale member is named from Rarden, Scioto County. It is not recognized outside the Vanceburg facies, since opportunity to identify its upper limit is lost with the disappearance of the overlying sandstones. Like the Henley member, it consists of alternating red and gray clay shales. At Vanceburg, Kentucky, it is $8\frac{1}{2}$ feet thick; from here northward and eastward it increases in thickness to 28 feet at Buena Vista, 27 feet at Rarden, 50 feet at Bainbridge, and about 58 feet at Elm Grove in Pike County on the extreme eastern margin of the facies.

Along the western margin of the outrcop belt, in Adams County, where the Buena Vista member becomes insignificant, this member probably rests on, and is indistinguishable from, the Henley member, although no section of precisely this type has been seen. At Mineral Springs, Adams County, there are something over 40 feet of red and gray clay shales at the base of the Cuyahoga, with a single 3-inch sandstone in the lower part, believed to be

the Buena Vista. This is the nearest approach to this condition observed.

The Vanceburg member consists of typical sandstones of the facies. It is best developed in the vicinity of Vanceburg, Kentucky (from where the name is derived), and Buena Vista. Here the member is about 150 feet thick and on the whole the sandstones are thicker than the intervening shales. Both northward and eastward the shales become relatively more important, and at Bainbridge they form much the larger part of the member. These sandstones give place by transition to the shales of the Scioto Valley facies, but rather abruptly, along the line indicated on the map.

The Churn Creek member is seldom seen and then not well. It consists of argillaceous shale with an occasional thin sandstone and the deposits of the Vanceburg member pass into it gradually. Except for the difference in relative amounts of sandstone and shale it is of the same type. It appears to be between 50 and 100 feet thick, but no section has been seen which admits of determination of this point. It is present in Ohio only in western Scioto and eastern Adams counties, being removed farther north, and only in the vicinity of Buena Vista is the Logan formation found overlying it. It is named from Churn Creek in the southeastern part of Adams County, on the divide between which and the head of Lower Twin Creek good outcrops are seen in roadside ditches.

THE CUYAHOGA FORMATION IN KENTUCKY

It has been shown how the outcrop belt of the Cuyahoga passes southwestward diagonally across the five successive facies from the Toboso facies in central Ohio to the Vanceburg facies at the Ohio River. From the Ohio River the outcrop belt of this formation continues southwestward into Kentucky. The writer has seen it at various points as far as the center of the state[1] but is not prepared to discuss it from such observation. Morse and Foerste have published sections from this region that indicate something of the

[1] Under grant from the Esther Herrman Research Fund of the New York Academy of Sciences.

nature of the formation,[1] but their sections are for the most part of the Bedford, Berea, and Sunbury formations. At a few localities only is more than the very base of the Cuyahoga described and in no one section is the entire formation distinguished.

From these observations it appears that there lies southwest of the Vanceburg sandstone facies in Kentucky an area in which the Cuyahoga is largely a bluish argillaceous shale, and that the margin between them lies somewhere between 5 and 20 miles south-southwest of Vanceburg, Kentucky. Not only do the sandstones that characterize the Vanceburg facies largely disappear, but the red shales that are equally characteristic are replaced by bluish ones. A sandstone member of precisely the same character as the Buena Vista member on the eastern side of the Vanceburg facies and occupying about the same position in the formation is continued to the southwestward into this shale facies. It is quarried at Farmer, Freestone, and Rockville, about 30 miles southwest of Vanceburg, where it is about 25 feet thick and is reported underlain by from 1 to 11½ feet of soft shales. Morse and Foerste consider this sandstone the top of the Buena Vista member, using that term with the sense given it by Prosser. Although it closely agrees with the Buena Vista member (sense adopted by the present writer) in structure and position, this correlation cannot, as yet, be considered established. Within 10 miles farther to the south-southwest, this member appears to pass into shales and the Cuyahoga is almost entirely a shale, but apparently with diminished thickness.

The question may well be raised whether these shales are the equivalent of the Cuyahoga formation, as it has herein been described, in southern Ohio. A careful tracing of the sandstone members in the lower part is necessary to an opinion as to whether the base is approximately the same. As to the upper limit, *Allerisma winchelli* was found by the writer in the overlying yellow sandstones, perhaps 100 feet above the shales, near Morehead, Kentucky. This species is, as far as known, confined to the Byer and Allensville members of the Logan. This would indicate that

[1] "The Waverly Formations of East Central Kentucky and Their Economic Values," *Kentucky Geol. Surv., Bull. 16* (1912), 76 pp.

the lower 100 feet at least of these sandstones in northern Kentucky, within 45 miles of Portsmouth, are the approximate equivalent of the Byer member in southern Ohio, which there overlies the Cuyahoga or in part passes into the topmost beds of the Cuyahoga.

PALEOGEOGRAPHY OF THE CUYAHOGA

The Toboso and Hocking Valley conglomerate areas.—Herrick thought that the material composing the Black Hand conglomerate came from the northeast.[1] Stevenson writes of the pebble material of the "Logan" (Orton's usage, Black Hand and Logan of this paper) as follows: "They can hardly have come from the north, for there the upper Logan, Reid's Olive Shales, is very fine in grain, while farther south it becomes coarse, as it is in northwest Pennsylvania, east from Reid's localities. It is equally improbable that the pebbles come from the east, for the deposits become finer eastward toward the central line of the basin, beyond which they become coarser. The sands must have come from the western side."[2]

The immediate source of the conglomeratic material in the Cuyahoga of central Ohio undoubtedly was to the south-southeastward. Lamb's observations in northern Ohio on conglomerates of undetermined horizon indicate the same direction as the source of the material.[3] It is not possible at present to state under precisely what conditions the conglomerate sandstones of the Toboso and Hocking Valley facies were deposited, but it is the writer's opinion that they are the result of deltal action under marine conditions. The structures observed, however, do not in any way correspond to the structures suggested by Barrell as criteria of such an origin.[4]

These sandstones were deposited under conditions of strong current-action which swept pebbles up to an inch in diameter to their present position; which laid down thick beds over wide areas at an inclination of 5° to 10° (much steeper than the foreset beds of the large deltas of the present, according to Barrell); which generated in these beds cross-bedding of the most pronounced kind,

[1] C. L. Herrick, *Bull. Sci. Lab. Dennison Univ.*, II, Part I (1887), 9, 10.

[2] J. J. Stevenson, *Bull. Geol. Soc. Am.*, XIV (1903), 91.

[3] G. F. Lamb, *Ohio Naturalist*, XIV (1914), 344–46.

[4] Joseph Barrell, "Criteria for the Recognition of Ancient Deltal Deposits," *Bull. Geol. Soc. Am.*, XXIII (1912), 377–446.

of both the irregular cut-and-fill and the regular inclined-bedding types; which, over extensive portions of the eastern side of the Hocking Valley area, dumped coarse conglomerate to a thickness up to 50 feet or more at an angle of from 15° to 20°, with northeasterly dips.

The material on the whole is far coarser than that observed, according to Barrell, at present in the deltas of large rivers, and the current-action was far stronger. It is the writer's opinion that the sands of the more gently inclined beds (5° to 10°), where cross-bedded as in the Black Hand member of the Toboso facies, were spread out on the ocean floor in part by the assistance of wave-action and shore currents, but chiefly under the direct influence of strong currents from a river mouth or other source of sand-laden waters. Where cross-bedding is reduced in amount and magnitude, as in the beds of the Fairfield member, the stream current is believed to have been relatively less important and the wave and shore currents more important. Much of the Black Hand member of the Hocking Valley facies has been laid down, according to this interpretation, under the former conditions, but large portions, especially near the margins of the facies, under the latter conditions. Where steeply inclined conglomerates with dips of 15° to 20° are extensively developed, as in the eastern portion of the Black Hand of the Hocking Valley area, it appears that the material was dumped into a protected area of relatively deep water, where it formed a face at the angle of repose for such material in water, uninfluenced by waves or bottom currents. A glance at the map will show that the eastern margin from Lancaster to Logan must have been, under the interpretation given these facies, well protected, and it is here only that such extensive steeply inclined bedding is found. It seems necessary to believe that the wave-action was far weaker than that obtaining along the seaward faces of present-day deltas facing the open ocean; otherwise this material would have been spread laterally along shore and outward to such an extent that the Toboso and Hocking Valley facies would not have remained as sharply defined, individual lobes.

The structures observed in the cross-bedded conglomerate, whether steeply or gently inclined, are precisely the ones that

Barrell regards as indicative of river-laid sands,[1] and not indicative of wave-laid or wave-current-laid sediments; but that they were accumulated under subaquatic and probably submarine conditions is indicated (1) by the rapid lateral passage of the members into marine beds; (2) by the presence of oscillation wave ripples on an inclined bedding-plane between sharply cross-bedded conglomeratic sandstones, in one case known over several acres and through a vertical range of some 30 or 40 feet; (3) by the presence of worm trails (*Scalarituba*) that are common in undoubtedly marine Waverly sediments; and (4) by the occurrence of thin beds of soft clay shale interbedded with the inclined sandstones and similarly inclined. No mud cracks have been seen and there is none of that evidence of oxidation seen in highly colored red beds, which may be the result of, and commonly are held to suggest, subaerial accumulation. To be sure, red sandstones occasionally appear, but they are not confined to one bed so much as to a limited locality where a considerable thickness of beds may be involved, and where, it appears, some other local condition or source must be involved.

The structures observed are very like those that would be expected in bars or spits built into deeper water, such as Sandy Hook, but perhaps with more cross-bedding; however, from the geographic distribution of the conglomerate masses along the belt of outcrop it is at present impossible to entertain this view. It does not appear possible for two such bars as the Hocking Valley and Toboso facies would imply to be built alongside of and parallel to each other simultaneously; and the results obtained so far all indicate that they were accumulated simultaneously.

As has been pointed out, there is distinct lobation in the Hocking Valley area; east of the Hocking River in southern Fairfield County, and traversed by it in Hocking County, is a secondary mass of conglomeratic sandstone that is immediately adjacent to the main mass of the facies, and it appears very probable that under cover of the Coal Measures to the southeastward the Toboso and Hocking Valley masses may become contiguous in the same way and prove to be only larger lobes of a yet greater development of coarse material. If the interpretation is correct that these

[1] *Op. cit.*, pp. 430–32.

sediments are of deltal origin, then the outcrop belt in central Ohio appears to be that portion of the floor of a marine interior sea which lay just off the front of a delta and was invaded by lobes from it. It appears, however, that no portion of the outcrop sediments have been deposited subaerially. The shoreline perhaps lay at no great distance to the southeastward, possibly only a few miles. The sea must have been one of quiet waters compared with the open ocean, otherwise the waves would have destroyed the fairly sharp lines of the facial boundaries.

It is, perhaps, unexpected to learn that these conglomeratic sandstones had their origin in the Appalachians. The paragraph quoted above from Stevenson's carefully considered work indicates how far it was from the thought of one who knew the whole problem. Certainly the deep-well records so far published from southeastern Ohio lead one to believe that the corresponding portion of the column under cover is largely shale. Well records, however, are very unreliable except when samples are taken, and usually but little attention is really paid by the driller to any except the few horizons that are well known to him and are used by him as guides.

It appears probable that, in certain places at least, the Cuyahoga sediments under cover in southeastern Ohio may be coarser than they have been described. However, it does not appear necessary to assume that the Cuyahoga under cover to the southeastward must be made up of similarly coarse sediments over wide areas. A great deal of coarse material, such as is found in either of these facies, might be transported through a relatively much smaller channel in fine-grained deltal sediments of an earlier stage of accumulation. To account for the conditions in this way would probably necessitate the assumption that there was a change in the nature of the material transported toward increasing coarseness, aggradation in proportion, and a consequent building out over the subaerial portion of the delta of a sandstone member of some thickness, but this thickness, it appears, would be thin in the lower courses of the delta.

The Vanceburg sandstone facies.—The Vanceburg facies was accumulated under conditions different from those of the Toboso and Hocking Valley conglomerate facies. Nevertheless, it probably

represents a phase of the same deltal action. Without much doubt the source was to the south-southeastward; it is not, however, inclined structure which indicates this, but the increase in the relative amount of sandstone in that direction. At one time the writer believed that the deposits of this facies were the offshore accumulations on the east side of the Cincinnati dome and that they were evidence that the dome at that time was land area. The rapid westward thinning of the Henley shale member at the base of the Cuyahoga supported this, and indeed, so far as the writer can see, can be interpreted only as indicating that the dome was at least an appreciable topographic feature on the ocean floor at the beginning of Cuyahoga time. It does not now appear, however, that the sandstone of the Vanceburg facies can be interpreted as evidence of a shore near by to the westward. The fact that in Kentucky, within a few miles of the Ohio River, a pure shale facies is found lying to the westward of this sandstone area with no red shale demonstrates that its general nature is that of a lobe of sandstone, pushed out into open water from the mouth of a stream or other definite source of sand, not an alongshore sand deposit. Indeed, nothing has been observed anywhere in Ohio or Kentucky which suggests that land lay to the westward in the region of the Cincinnati dome.

It is possible that local conditions, for example stronger wave- and ocean-current action, will explain the structures found in these sandstones, so widely different from those of the conglomerate facies. But better still is the assumption that the stream currents (or whatever other local current may have been the source) that fed these sands were far weaker than in the Hocking Valley and Toboso areas; the wave-action being the same, under such conditions the feeble waves of this sea might well have been better able to distribute the fine sands brought in at this point, whereas in the conglomerate areas the stronger feeding currents, with their loads of coarse pebbly sand, locally dominated over the wave-action.

The source of the material.—It is of interest to note the nature of the nearest sediments of this age which are exposed to the southeastward and southward as a possible source of the material. The Waverly formations occupy the same interval in the geological

column as the Pocono sandstone formation of the Appalachians and are generally regarded as its approximate equivalent. The Pocono sandstone is exposed in various belts in the Appalachians from the anthracite fields southwestward through central Pennsylvania, the western part of Maryland, and on both sides of the boundary line between Virginia and West Virginia to a point in Virginia south of the southern part of the last-named state.

The following paragraph is presented as a brief summary of the published accounts of the Pocono in this region and of a new interpretation of the members forming it; it appears that the irregularity in thickness and composition of the Pocono at various points in northeastern West Virginia can be understood on the theory that there was there erosion of its beds to the extent of 1,100 or 1,200 feet prior to the laying down of the Greenbrier limestone.

It appears that the Pocono in northern Virginia, western Maryland, and south-central Pennsylvania consists of four members (a fifth higher member has been reported from a single locality), of which the second one in ascending order is a prominent gray or white conglomeratic sandstone, the Purslane sandstone.[1] It appears that this sandstone-conglomerate member is the one which comprises almost the whole of the so-called Pocono in its thinned more westerly outcrops along the line between Virginia and West Virginia and in West Virginia, and that there the underlying member has heretofore generally been included with the Catskill.[2] In western and southwestern Virginia, three members have long been recognized[3] which, it appears, correspond very closely to the uppermost three in northern Virginia (excluding the seldom-observed highest member), and the massive conglomerate sandstone at the base in southwestern and western Virginia corresponds exactly with the second member or Purslane sandstone to the northward. It further appears that there is beneath this sandstone in western and southwestern Virginia a member, closely corresponding to the lowest member or Rockwell to the northward, which has been

[1] G. W. Stose, Pawpaw-Hancock Folio, No. 179, *U.S.G.S.*, 1912.

[2] Piedmont, Accident-Grantsville, Franklin, Staunton, Monterey, Buchannon Folios, *U.S.G.S.*

[3] W. M. Fontaine, *Am. Jour. Sci.*, 3d ser., XIII (1877), 115–16; J. J. Stevenson, *Bull. Geol. Soc. Am.*, XIV (1903), 29, and citations there given.

doubtfully referred both to the Pocono and to the Catskill, more latterly to the Catskill. So far as the writer is aware, this correlation between the members in northern Virginia and those seen to the southwestward has not before been suggested. If it is a correct one, then the Purslane sandstone member, the second member in northern Virginia, becomes important, not only as a very persistent member along the Appalachian belt, but as the only member of the Pocono along the line of the Appalachian mountains that is comparable with the coarse sandstones and sandstone conglomerates of the Cuyahoga along the Waverly outcrop belt in Ohio. When it is further recalled that the structure of these Cuyahoga sandstones and conglomerates proves that they were derived from the south-southeastward, and that the axes of the facies point in the same direction, the possible correlation with the Purslane becomes doubly suggestive. It remains to question whether the whole of the Cuyahoga sandstones should be correlated with the Purslane, or only the upper or Black Hand member, which alone is notably conglomeratic. The question is at present too uncertain a one to discuss, but if it be found that the Black Hand alone should be so correlated, the broad extent of the member would be the only cogent argument yet put forward for the separation of the Black Hand from the remainder of the Cuyahoga sediments.

LOGAN FORMATION

The simplicity of lithological structure and stratigraphy of the Logan formation is in marked contrast with the extreme variability which is found in the several facies of the Cuyahoga. With the opening of Logan time, the localization of conditions which resulted in widely different sediments in closely adjacent areas during Cuyahoga time gave way to quite uniform conditions over the whole of the southern Ohio Waverly belt. Extreme areal variation with no very important variation in vertical succession was succeeded by widespread areal uniformity and a threefold vertical subdivision which can be recognized from the Ohio River to the center of the state and probably well into northern Ohio.

Subdivisions and extent.—The three subdivisions of the Logan formation in descending order are as follows: Vinton member, Allensville member, Byer member.

It is possible that a fourth member should be recognized. E. B. Andrews in 1878 proposed that certain beds at the top of the Logan formation at Rushville be designated the Rushville[1] group. There are there shown 22½ feet of rather soft argillaceous shales, gray or red in color, of a type quite different from the bulk of the sandy sediments that compose the Logan, and a pink crinoidal sandy limestone one foot thick. These beds are stratigraphically much higher than those which usually form the top of the Logan. This is because the pre-Pennsylvanian erosion surface here stands, relative to the beds it cuts, much higher than in most places. In addition, these beds were stated by Whitfield to show certain faunal peculiarities that, if verified, will distinguish them from the remainder of the Logan. The fauna has been extensively collected but no statement can be made as yet.

Although the three members listed above are found throughout the length of the Logan belt from central Ohio to the Ohio River, they are not present throughout its entire breadth, as is shown by the map (see Part I) of the known distribution of the Allensville member. In Scioto County the western limit of this bed is quite definitely known. In Pike and Ross counties its absence from the western half of the Logan belt is not demonstrated because of covered slopes and absence of outcrops, but such absence is very strongly suspected. It is in part on the presence of this member that the subdivision depends. The upper member is occasionally absent because of erosion prior to the deposition of the Pennsylvanian or Coal Measures; yet more rarely all three have been removed.

The lower and upper members are fine-grained sandstone and shale deposits, the result of quiet, uniform conditions; the Allensville bed is a very coarse sandstone, or perhaps it would better be called a fine pebble bed, the result of an interval of contraction of the basin. The whole is marine throughout, although faunal remains may be rare.

The Byer member.—This is usually a fine-grained sandstone. Its beds are seldom over 18 inches thick and may tend to split up into thinner beds. In southern Ohio, and especially in the more

[1] *Am. Jour. Sci.*, 3d ser., XVIII (1879), 137.

westerly outcrops, portions of it are better described as shaly sandstone or sandy shale. Even where it is wholly a sandstone there is enough clay present to make the sandstones soft. The color as seen on the outcrop is almost invariably yellow or buff, but under sufficient cover it is probably always a shade of blue or gray. At two points only within the area herein considered is it sufficiently massive to be quarried, at Newark and at Granville in Licking County. At the former locality the beds may attain a thickness of three or four feet.

The member is named from the town of Byer in the northern part of Jackson County where it is well shown in the railroad cuts east of the village. It agrees very closely in its upper and lower limits with the Division II or Kinderhook of Herrick, and with that portion of Prosser's Black Hand at Newark lying between Conglomerate I (the Berne member) and Conglomerate II, the latter one of the beds of the Allensville member.

The coarseness of the material is influenced appreciably by the presence below it of the conglomerate masses of the Cuyahoga, especially in Licking County. The thickness has been considerably influenced. Over the northern counties, Licking, Fairfield, Hocking, and Vinton, where conglomerate sandstones constitute the most of the Cuyahoga and the thickness is correspondingly great, the Byer member is much thinner than farther south in Ross, Pike, Jackson, and Scioto counties. Where the two conglomerate areas are thickest it is 25–30 feet thick; over the intervening Granville province, where the thickness of the Cuyahoga is somewhat reduced, it is commonly about 50 feet and at one point it reaches 80 feet. Westward and southwestward from the great Hocking Valley conglomerate area, as the thickness of the Cuyahoga decreases with its passage into shale the thickness of the Byer member steadily increases from 23 feet to at least 154 feet in eastern Pike County.

The tendency of the Byer sandstones to pass into shales toward the westward, although noticeable in Ross, Pike, and Scioto counties, is most pronounced along the Ohio River. There, between Sciotoville and Portsmouth, the lower portion, to a thickness of at least 75 feet and perhaps more, passes into shales which are not distinguishable from the body of the Cuyahoga shales of

the Scioto shale facies and which have been considered the upper part of the Portsmouth member of the Cuyahoga. This tendency on the part of the Byer sediments suggests strongly that its material was also derived from the eastward and southward, in spite of the thinning of the formation to the eastward.

It is not possible to say to what extent the member continues to thicken westward because of the disappearance of the Allensville member in that direction just where the Byer passes into shales and sandstones which are lithologically so similar to those of the Vinton member as to be indistinguishable from them.

The Byer member was formed during a period of quiet sedimentation. The shoreline lay far enough to the eastward so that the outcrop belt of central and southern Ohio was wholly outside the zone of continual shifting of sands by currents and waves, and beyond the reach of delta or sand-spit accumulations such as are seen in the Cuyahoga. Sharp contacts between beds are seldom observed where shaly sandstones make up a considerable part of the succession, the change from sandstone beds through shaly sandstones to shale beds being almost always a gradational one. Well-defined bedding-planes are more likely to be found in those portions made up almost entirely of sandstones and where the material is slightly coarser, as in central Ohio. Although the conditions of sedimentation are best described as quiet, the abundant sediment making up the member was probably swept to its present position and distributed largely by gentle current-action and not by subsidence from mechanical suspension in the water. The material is too coarse to be carried any distance in that way. The presence of such gentle current-action is shown, for example, (1) by frequent cross-bedding in the finest material with long, gently sweeping stratification planes, and (2) by the local sweeping together into a heap of such an odd aggregation of species and abundance of individuals as was found in three cubic feet in a certain bed at Sciotoville, which is otherwise practically barren of fossils, although excellently shown for half a mile and 30 feet thick.

If the correlations made by Cooper in sections to the northward be accepted, the Byer member continues little changed and from 25 to 40 feet thick for at least 55 or 60 miles to the northward of

central Ohio, into Wayne County.[1] This is to within 40 miles of Lake Erie.

The Allensville member.—The quiet conditions of Byer time were terminated by general shoaling of the region which resulted in the formation of the Allensville bed, whose chief characteristic is its coarse sandstones. Over much of the area this was brought about gradually, since there is a transition from one to the other; in fact, the typical sandstones of the Byer type are found almost to the top of the Allensville.

The name Allensville is given from numerous outcrops near that village in the western part of Vinton County, although the bed is not especially well developed there nor any better exposed than at other points. As is shown on the map (see Part I), it is found from the Ohio River as far north as the work has been pushed. In Scioto County along the river it is known certainly that it disappears westward, thus demonstrating that the source of its material lay to the eastward. In Pike and Ross counties this westward disappearance has not been completely demonstrated because of poor outcrops, but it is almost certain.

The greatest thickness yet observed is 39 feet, reported by Mr. Schroyer in Pike County, but this is exceptional. Commonly it is from 15 to 25 feet throughout the whole area but not infrequently it is less. It is least on the Ohio River near its extreme western limit where it diminishes rapidly from 6 feet to as many inches just before its final disappearance. The bed is apparently present at every point within the area of its occurrence indicated on the map.

As just noted, its chief characteristic is the occurrence of very coarse, excellently assorted, and usually well-rounded quartz grains. South of Fairfield County the material of the coarse beds is really a fine conglomerate of excellently assorted pebbles from one-sixteenth to one-eighth of an inch in diameter. The coarse beds there first appear in the section as thin layers, often only an inch or less in thickness, between much thicker beds of the typical, Byer-like sandstones. It is very difficult exactly to locate the base if the outcrops are poor. Much of the lower part of the member

[1] *Bull. Sci. Lab. Dennison Univ.*, V (1890), 24–32.

might well be considered the last stage of the Byer, but the lowest occurrence of the coarse beds has been adopted as the base of the member, even though this may not be the same particular streak that has been observed at the supposed base in a closely adjacent section. The coarse beds become more numerous and thicker in passing upward and usually make up the greater part of the upper half of the member. The topmost 3–5 feet of the member are almost invariably made up of these coarse sands to the almost complete or complete exclusion of the fine-grained material. At all points these coarse deposits carry unusually large amounts of iron, their cement being largely limonitic. This feature alone is often sufficient to identify the horizon. In southern Ohio, beyond the fact that the topmost bed is always the thickest, it is not possible to recognize the beds from section to section.

In Fairfield and Licking counties the material is noticeably finer. Whereas to the southward the beds may be described as made up of small pebbles, from Hocking County northward the component material can only be called coarse sand. The assortment is good and there is no notable admixture of the coarser material except in certain limited beds.

In eastern Fairfield County and central and eastern Licking County a characteristic feature of the member is the remarkable persistency of its beds. In its thickness of 15–25 feet, four distinct submembers can be recognized, all more or less persistent and with more or less distinct faunules. This condition is not found to the southward. Following is the section of the Allensville member as exposed in the Vogelmeir quarry at Newark; beds 1, 2, 4, and 5 can be recognized with considerable variation from Rushville to Newark, beyond which they have not been followed. Both Nos. 4 and 5 are likely to have lenses of coarse sand developed in them extensively and No. 5 at Rushville is largely of such coarse material.

	Ft.	In
5. Moderately fine-grained, irregularly bedded, yellow sandstones with numerous beds of coarse, reddish, iron-stained sandstone, the last mostly in the upper half, fossiliferous	14	
4. Bluish-gray, argillaceous shale, little grit, fossiliferous	3	9

	Ft.	In.
3. Coarse quartz sandstone, grains well sized and rounded, white in color, harder and with much less iron than the other beds. This is Conglomerate II of Herrick and the bed which forms the top of the Black Hand in Prosser's description of this section.....		½–6
2. *Allerisma winchelli* horizon, a hard, bluish, gritty shale with a considerable fauna, chiefly of lamellibranchs and abundant *Spirophyton* markings, one of the most important horizons in central Ohio.....	5	
1. Very coarse, loosely coherent, reddish sandstone, grains uniformly sized and all about one millimeter in diameter, rounded or subangular. Lower surface slightly irregular.....	1	4

Evidence of erosion of the underlying beds before some of the coarse members were laid down is not unusual. Both at Rushville in Fairfield County and at Newark the topmost bed of the Byer sandstone had been eroded slightly before the basal bed of the Allensville was laid down. The fossils in the *Allerisma* shales are practically always found in the attitude which they maintained during life, the shells of *Prothyris* standing vertically with the anterior end downward, the shells of *Allerisma*, *Grammysia*, and *Sphenotus* standing obliquely with the anterior end downward. At Newark these shells have been observed at the top of the *Allerisma* shale with the upper portion beveled off at the contact with the overlying coarse bed (Conglomerate II). Evidence of erosion is also seen at the base of some of the higher coarse lenses when they are well developed. Obviously the erosion observed in connection with most of these beds is local. This urges caution in accepting the erosion which took place prior to the formation of the lowest bed as any more important. It is, however, probably of somewhat greater significance since in central Ohio it inaugurated an abrupt change in conditions of sedimentation. In the southern counties no evidence of such erosion has been seen, and the change in the conditions of sedimentation was more gradual. Among numerous interesting problems is the occurrence of these slight erosion surfaces associated with the finer beds of the member, whereas to the southward where the beds are coarser the evidence of erosion, if present at all, is less prominent.

Curious and probably of considerable significance is the manner in which the Allensville bed disappears from the column in southern

Ohio. At Slocum Station, 2½ miles east of Sciotoville, the Allensville bed is well developed, with a thickness of 13 feet 4 inches. Of this the uppermost 4 feet 3 inches are composed almost wholly of the typical fine conglomerate which characterizes this member in southern Ohio. Three-fourths of a mile southwest of this locality only 2 inches of typical Allensville pebble material is present in a section sufficiently clear to show that no other beds of this type are present. A mile and a quarter west of Slocum Station only the merest trace of the Allensville member is present in the form of a few quartz pebbles of usual size in a 2-inch zone of fine-grained sandstone. At Sciotoville there is no evidence of its presence or suggestion of its proper horizon, although repeated search has been made for it in good sections. Not only are the pebbles wanting from this section, but there is no bed of coarse sandstone or bed of any description, which by any character suggests that it may be the westward extension of the Allensville bed. That member completely disappears from the Logan formation certainly within 3½ miles and probably within 2 miles, with no tendency to grade into finer beds.

The Vinton member.—This is the youngest member of the Waverly series. How much more there may have been at one time is not known, since the Vinton is limited upward at all points, where it has not been entirely removed, by an erosion surface, a horizon of great unconformity.

The Vinton member is named from Vinton County, where it is well developed, although not nearly so well developed as elsewhere. It is a series of fine-grained gray or yellowish sandstones and shales. It differs from the typical Byer in the presence of shale beds and in the thinner bedding and more platy nature of the somewhat harder sandstones. However, as noted under the Byer member, these members come to resemble each other very closely in southern Ohio.

Although no especial effort has been made to trace them, it is very evident that certain of the beds composing this member are quite persistent areally. This not only indicates the uniformity of conditions which prevailed but may have yet a greater significance, since there is considerable faunal difference in certain of the

different beds. For example, at the base of the formation from central Licking County southward at least as far as western Vinton County, a distance of 55 miles, there is a 30- to 40-foot bed of sandy shales with no particular faunal characters noted as yet. It is overlain at all points by a bed of fine-grained yellow sandstones with an abundant fauna, of which one of the chief species is a *Productus*, heretofore described as, but distinct from, *Productus arcuatus* Hall.

The Vinton member marks the resumption of conditions of quiet, uneventful deposition in deeper water, following the period of shoaling which resulted in the formation of the Allensville member. There is no transition from the one to the other. The shales of the former rest abruptly on the coarse beds of the latter at all points, and this contact is one of the sharp and persistent ones in the Waverly series. It is suspected that its significance as a stratigraphic horizon is more or less in proportion to this prominence.

The thickness of the Vinton is determined wholly by the attitude of the post-Waverlian erosion plane. Valleys of considerable depth were cut into the Waverly following its deposition and prior to the accumulation of the Pennsylvanian deposits, or Coal Measures, and considerable irregularity can be detected in its upper surface as a result. The greatest known thickness of the member is preserved in the northwest portion of Perry County and adjacent parts of southern Licking County. Here was an area which must have been uniformly high land, for the Vinton member is from 200 to 240 feet thick, although it does not usually much exceed 50–75 feet thick, and is occasionally wholly removed. On the Ohio River between Sciotoville and Portsmouth the member probably attains a similar thickness, but precise determination is seriously hampered by the absence of the Allensville member. The Mississippian-Pennsylvanian contact in central and southern Ohio has been briefly described.[1]

[1] J. E. Hyde, "Notes on the Absence of a Soil Bed at the Base of the Pennsylvanian of Southern Ohio," *Am. Jour. Sci.*, 4th ser., XXXI (1911), 557–60.

REVISION OF THE MAP OF LAKE AGASSIZ

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After the lapse of twenty years since the completion of my official service on the geological surveys of Minnesota and the United States, it is not surprising that changes and additions have been made, and that others are needed, on maps of the glacial and modified drift formations and the successive shorelines of the glacial Lake Agassiz, as these were published in the reports of my work from 1879 to 1895. Therefore the recent *Bulletin 12* of the Minnesota Geological Survey,[1] entitled "Surface Formations and Agricultural Conditions of Northwestern Minnesota," by Mr. Frank Leverett, of the United States Geological Survey, has much interested me.

One of the most noteworthy additions here made to our knowledge consists in the more accurate description and mapping of the somewhat elevated large tract between Red Lake and the Lake of the Woods, which was named by me Beltrami Island.[2] My original description and map of this island were doubted and questioned by Professor James E. Todd in 1899;[3] and they have now been shown by Mr. Leverett, with more definite surveys, including information of exact altitudes throughout this area, to need important revision.

A line surveyed about the year 1892 for the Duluth & Winnipeg Railroad Company took a straight northwesterly course from the most northeastern part of the shore of Red Lake to the most south-

[1] This report, 78 pages, with 8 plates (a folded map and views from photographs) and 14 figures in the text (maps and diagrams), was published by the University of Minnesota in February, 1915, under Professor William H. Emmons, director, in co-operation with the United States Geological Survey. It includes also a chapter on "Climatic Conditions in Minnesota," by U. G. Purssell, United States weather observer in Minneapolis.

[2] *Am. Geologist*, XI (June, 1893), 423–25; "The Glacial Lake Agassiz," 1896, *U.S. Geol. Survey Mon. XXV*, 304–06, with mapping on Plates III, X, etc.

[3] *Geology of Minnesota*, IV, 149–50.

western part of the Lake of the Woods, at the present station of Warroad. Through a distance of 18 miles next northward from Red Lake this survey traversed a continuous swamp, called on the profile "tamarack and spruce swamp," which includes the divide between the basins of this lake and the Rainy River. The depth of the mud and water throughout the swamp was from 5 to 15 ft., being mostly between 7 and 10 ft.; and in many places the hard bottom was noted as gravel and sand. The highest part of the surface of the bog or swamp on this line, forming the water divide, some 5 to 6 miles north of Red Lake, has an elevation of 1,197 ft. above the sea, being 21 ft. above the lake. Westward from this lowest part of the divide on the north side of the basin of Red Lake and the Red Lake River lies the area of Beltrami Island, of which the northeast margin was crossed by this railroad survey, rising there to a height of 1,283 ft., or 107 ft. above Red Lake and 86 ft. above the eastern base of the island.

The profile of the surveyed line shows a well-defined beach of Lake Agassiz at 1,215 ft., this being the highest recognizable beach ridge crossed by the survey. On the descent toward the Lake of the Woods the profile crosses a succession of ten lower beaches of the great glacial lake, their altitudes above the sea being 1,196, 1,172, 1,156, 1,143, 1,127, 1,116, 1,106, 1,099, 1,093, and 1,087 ft.[1]

These beach ridges are clearly indicated by the profile, but none are shown at higher levels. My conclusion from the profile record, therefore, was that the series comprises the highest shore and the successively lower shores of Lake Agassiz. The higher part of the tract northwest of Red Lake was accordingly called an island of that glacial lake, and was named, like the county in which it mostly lies, for the exiled Italian author, Costantino Beltrami, who in 1823 was one of the earliest white men to traverse and describe this region. He was preceded only by the Canadian geographer, David Thompson, in 1798.

An elaborate map of this area, from Red Lake north to Rainy River and the Lake of the Woods, with contour lines at intervals of 10 ft., accompanies a report published in 1909,[2] entitled "Drain-

[1] Notes of this profile were published in *Geology of Minnesota*, IV (1899), 136–37.

[2] 61st Cong., 1st sess., *H. R. Doc. No. 27*, 40 pages.

age Survey of Certain Lands in Minnesota." These lands, ceded by the Chippewas, were surveyed in 1906–8, for the United States Geological Survey, under direction of W. H. Herron, geographer. On the large map of this report the contour of 1,200 ft. above the sea incloses a tract of 1,167 square miles, its most southern point being 4 miles north of the mouth of Red Lake, and its most nothern point 2 miles south of Roosevelt, on the Canadian Northern Railway, and about 9 miles south of Muskeg Bay, the most southwestern part of the Lake of the Woods. This large tract, nearly flat or somewhat undulating, rising to a maximum elevation of 1,310 ft., would be an island if the conditions that produced Lake Agassiz were now restored with the lake level at 1,200 ft.

Beltrami Island, as thus outlined, however, differs much from its mapping in the Lake Agassiz monograph; for on the west it falls short, by 12 miles, from reaching to Thief Lake, which had been included in the tentative original map of the island area. But the beaches bordering the island have been only partially mapped; and when this work shall be completed by leveling they will show an ascent northward, or almost northeastward, like the other mapped shores of the old glacial lake. Appealing to the mapped gradients of the Herman shorelines from the south end of Lake Agassiz north to Maple Lake and eastward past the south side of Red Lake, Mr. Leverett well concludes that the highest Herman beach, if it is represented on Beltrami Island, must sweep with its northeastward ascent well-nigh above the entire island, touching only its highest ground, in Tp. 159, Rs. 35 and 36.

Even the second, third, and lower Herman beaches, mapped in succession at slightly lower lines to an entire number of seven on the west side of Lake Agassiz in southern Manitoba, may all be referable, as Professor Todd suggested, to water planes above the beaches at 1,215 and 1,196 ft. on the railway profile crossing the northeast edge of Beltrami Island. My original supposition that much of this island was above the highest level of Lake Agassiz has been needfully corrected by Mr. Leverett in this report.

Whether any of the Herman shores was marked on the island must depend on the position of the ice border in northwestern Minnesota when the glacial lake fell to its Norcross stage, which,

like the Herman stage, and like the lower Tintah, Campbell, and McCauleyville stages, becomes subdivided in its extension northward before reaching the International Boundary at the west side of Lake Agassiz. In my examination and studies of these shorelines for the geological surveys of the United States and Canada, the whole series of seven Herman beaches was regarded as yet present so far north as on the boundary between North Dakota and Manitoba, 224 miles north of Lake Traverse; but the two upper Herman beaches were thought to cease before coming to the latitude of Gladstone and Neepawa, in Manitoba, 308 miles from Lake Traverse and the mouth of the glacial lake. On Valley River in Manitoba, between the Riding and Duck mountains, 150 miles north of the international boundary and 375 miles from Lake Traverse, all the Herman beaches had ceased, according to my tabulation and correlation of the notes of Mr. J. B. Tyrrell, of the Canadian Geological Survey; but the Norcross, Tintah, Campbell, and McCauleyville beaches seem to be represented there by his observations.[1]

The discrepancy between my estimates and those of Mr. Leverett for the place or height of the Herman beaches north of Red Lake comes partly from his better determination of the large easterly component in the direction of maximum uplift and present ascent of the ancient lake-levels, which in their continuation eastward of Maple Lake trends increasingly toward the northeast. In manuscript notes on a map kindly supplied to me, Mr. Leverett records a well-defined beach of Lake Agassiz, 1,297–1,300 ft. above the sea, on the Minnesota & International Railway about 4 miles northeast of Gemmell, or 25 miles east-southeast from the north part of Red Lake. This is the highest of the Herman series there, and its rate of ascent from the vicinity of Maple Lake justifies the belief that has been already stated concerning the occurrence of the Herman shorelines on the area of Beltrami Island.

It is to be noted further in this connection that the trend of the Late Glacial uplift of the land and consequent ascent of the old beaches, near Red Lake and the Rainy River, now found to be N. 35° E., carry the conspicuous Campbell beaches farther east

[1] *U.S. Geol. Survey Mon. XXV*, pp. 476–77.

than my mapping in the United States Geological Survey monograph. The incoming of settlers, with the construction of roads and railways and clearing away the forest in many places to open farms, now gives opportunity to trace the courses of the beaches through the country adjoining the Rainy River, where Mr. Leverett maps a finely developed shoreline, referred to the Campbell stage of Lake Agassiz, for the distance of about 40 miles, from near Roosevelt east-southeastward to Baldus, having the height along all this isobasic course of about 1,120 ft. above the sea. This altitude is as great as the highest of the Campbell beaches has on the eastern slope of Riding Mountain in Manitoba, which shows that the isobase of the land uplift there crossing the lake area runs about N. 55° W. In other words, the direction of maximum uplift is approximately N. 35° E.

With the light thus received, we may quite confidently correlate the series of eleven beach ridges noted by the profile on Beltrami Island and northward, from 1,215 to 1,087 ft., as representing the second Norcross, Tintah, and Campbell stages of Lake Agassiz, but with other subdivisions than were noted in my tabulation for the latitudes of Gladstone and Valley River, Manitoba.

The present report and its large detailed map of the surface formations of the northwest quarter of Minnesota, on the scale of 8 miles to an inch, are designed primarily to instruct and aid farmers, drainage engineers, road-builders, and others, for the development and utilization of the agricultural resources of this state.

Glacialists and other geologists will desire that Mr. Leverett present later, for the entire state of Minnesota, a more specific description and discussion, and additional maps, setting forth the successive borders of the waning ice-sheet, as shown by their moraines, with the corresponding stages of growth of Lake Agassiz, and treating fully of the erosion, transportation, and deposition of the various drift formations. Such maps will be much improved by insertion of contour lines, and by notations of altitudes of lakes, rivers, railway stations, etc., whereby the form of the land surface and the elevation above the sea will be shown, giving information that seems indispensable for a definite understanding of the drift, loess, and glacial lakes.

Reviews

Geology of the Nome and Grand Central Quadrangles, Alaska. By FRED H. MOFFIT. Bull. U.S. Geol. Surv. No. 533, 1913. Pp. 136.

The Nome and Grand Central quadrangles are situated in the south-central part of Seward Peninsula in an area included between 165° and 165°30′ west longitude and 64°25′ and 64°57′ north latitude. The Tigaraha schist which is the uppermost member of the Kigluaik group (early Paleozoic and possibly in part pre-Paleozoic) is the oldest formation exposed. One principal granite mass and smaller dikes and sills intrude this schist. The relation between the Tigaraha schist and the overlying Nome group appears to be one of conformity. The Nome group (probably middle Paleozoic) makes up the greater part of the mapped area. It consists of two schist horizons with an intervening limestone formation. These beds are cut by greenstone dikes and sills and to a small extent by granite. Quaternary (possibly including some Tertiary) deposits that consist of marine and fluvial sands and gravels and glacial débris succeed the Nome group. The mineral wealth of the Nome district lies in its placer deposits. The richest of these are rapidly decreasing, so that the present production can be maintained only by new and better methods. The placers are described as residual, stream, beach, and gravel plain. Dredging will play an important rôle in the future development. A historic outline of the Nome placer development is given. There are gold, stibnite, bismuth, scheelite, copper, and graphite lodes, but these are at present not of commercial importance.

V. O. T.

Coastal Glaciers of Prince William Sound and Kenai Peninsula, Alaska. By U. S. GRANT and D. F. HIGGINS. Bull. U.S. Geol. Surv. No. 526, 1913. Pp. 72.

The aim of this report is to "supply some definite information regarding the present positions of the fronts of the glaciers" of Prince William Sound and Kenai Peninsula and "the more evident facts of their fluctuations." The Barry, Surprise, Chenega, Princeton, and Holgate glaciers have retreated from one to two miles within from 10 to 50 years or more. Since the growth of the present coniferous forest, the Columbia and Bainbridge glaciers have recently advanced to their maximum positions. The glaciers on the west side of College Fiord and Harvard Glacier have been advancing for the past ten years; their maximum advance was in 1905. Many of the glaciers have exhibited alternate advances and retreats of notable extent. There is no indication of a general advance or retreat during the last 50 years. These glaciers are remnants of an ice sheet whose upper surface once reached an elevation of 2,000 feet at the main coast line. The accompanying photographs (that constitute 40 plates) of the glaciers are exceedingly good and instructive.

V. O. T.

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